Exploiting Semi-Directional Transceivers for Localization in Communication Systems

THESIS

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Abstract

Localization is the process of determining relative, as well as absolute, positions of communicating devices. Traditionally, the process is conducted using range or directional estimates. In contrast, this research uses weak information to form relatively tight bounds on possible locations of communicating devices. Under certain conditions, achieved location estimation results are strong. However, these results are highly sensitive to the operating conditions of the proposed networks. More significant results were obtained from specialized cases and that the application yields somewhat limited information for a general randomized network topology. Feasible localization results were found to be attainable but not necessarily practical for multiple experiments. This is due to the brute force nature of the implemented localization algorithm which experiences an exponential increase in runtime as the number of nodes increases.

Acknowledgements

I would like to express my sincere thanks to my thesis advisor, Maj. Scott Graham. Without his persistence in pursuing this topic, it very well may not have seen completion. I learned a lot and I'm sure he did too.

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And last but not least, to Mom and Dad, who have always supported my ideas and decisions. This would not have been possible without you, as such, this thesis is dedicated to you.

Andrew S. Crockford

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EXPLOITING SEMI-DIRECTIONAL TRANSCEIVERS

FOR LOCALIZATION IN COMMUNICATION SYSTEMS

I. Introduction

1.1 Chapter Overview

This chapter presents the need for sensor network localization, a description of the problem, and how semi-directional communication may be exploited for localization.

1.2 Background

Sensor networks have been a focus of military, as well as civilian, research for a number of years. The United States (US) military has a particular interest in this area for its many battle-space applications. In one scenario, an aircraft, such as a C-130, may drop numerous tiny sensors into a selected location for information gathering. Depending on the functionality of the sensors, applications could include relay of movement tracking, weather analysis, sound detection, and communication.

However, the sensors (also known as nodes) that provide the functionality require location information, especially if events such as movement tracking or communication relay are expected to perform successfully. The process that determines node location is called localization. A network needs to be able to localize itself using only network resources because little to no outside resources are available to the localization process. This presents an inherent difficulty because nodes dropped are randomly placed into their locations, e.g., deployed by a C-130.

Localization can be accomplished using node transceivers. If these devices are directional, such as line-of-sight infrared or directional radio transceivers, this information can be exploited in the localization process. When two nodes are able to

communicate with each other, they have some information regarding each other's relative locations. Aggregating this pairwise information throughout a connected network constrains possible node locations for nodes within the network.

An immediate problem this approach creates is a map of potential node locations will require significant computational power to exploit. For instance, assume three nodes A, B, and C, are communicating such that a connection exists from A to B and from B to C. Let A's position be known and suppose A calculates a certain number of B's possible locations. Since B is not localized to a specific position, ambiguity exists in its potential locations. If B were used to calculate C's locations, potential locations for C must be calculated for every potential position of B. The greater the ambiguity in B's locations, the more potential locations of C. This can be mitigated to an extent and with certain refinement steps, more accurate results can be obtained.

1.3 Problem Statement

In many localizations systems the communication transceivers make estimates, however imprecise, of either the distance between nodes, the relative angle towards the node, or both. The use of such information is called triangulation or trilateration and will be discussed in Chapter 2.

This research uses a much weaker set of information derived from inexpensive transceivers. That is, a transceiver is assumed to have a minimum and maximum communication range, as well as a known field of view. The only information available to the localization routine is the presence or absence of communication. The goal of this research is to determine useful information from this weak information, and in particular, under what operating circumstances this may be useful.

1.4 Research Objectives, Hypothesis, and Questions

The objective of this research is to show that localization via short range directional communication is feasible. A system should be able to localize itself using only

a small amount of *a priori* information and a few assumptions. These assumptions include relative transceiver angles (of a given node) and perhaps known locations for a small number nodes (two nodes in this research), known communicator range information for all nodes in the network, and the link layer connectivity (which in direct communication). The hypothesis is the localization process can provide feasible localization results using weak information. The questions to be answered are:

- Is the algorithm practical for randomly generated scenarios of large-scale networks?
- Are the run-times for each simulation practical for general cases?
- Are results for multiple refinements of potential node locations significant enough to be useful?

1.5 Preview

Chapter 2 discusses the fundamentals of localization and map growing, sensor networks, and background information for infrared communication devices (the primary assumed communication method). Additional discussion on current research applications is also provided. Chapter 3 defines the localization methods used in this research as well as how the implemented algorithm functions. Outlines of the experiments are provided. Chapter 4 provides results and analysis for the experiments. Lastly, Chapter 5 provides a summary of the results, the significance of the results, and recommendations for future work in directional communication localization.

II. Literature Review

2.1 Chapter Overview

In this chapter, background information is provided. Topics include localization, sensor networks, and infrared communication. Current applications and research in some of these topic areas is also discussed.

2.2 Localization

Localization is a method of determining the location of an entity, e.g., a node in a network or vehicle in an automated traffic situation [12]. The process is typically accomplished through geometric means. There are two primary methods of localization: triangulation and trilateration.

Triangulation calculates the position of an object using information gathered from two other objects (i.e., nodes). For example assume three nodes, A, B, and C, as depicted in Figure 2.1, and the location of node C is to be determined. If the distance $\overline{AB}$ and angles a and c are known, the position of C is uniquely determined though simple trigonometry.

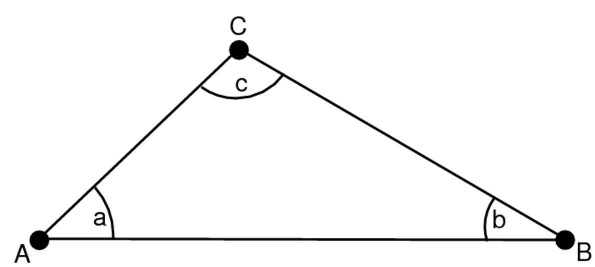


Figure 2.1: Example of Triangulation.

In fact, position of C can be calculated using the law of sines

$$\frac{\sin a}{\overline{BC}} = \frac{\sin b}{\overline{AC}} = \frac{\sin c}{\overline{AB}} \tag{2.1}$$

or the law of cosines

$$\overline{BC}^2 = \overline{AC}^2 + \overline{AB}^2 - 2\overline{AC} * \overline{AB}\cos a. \tag{2.2}$$

In a sensor network, angle information is often determined through a specialized antenna capable of sensing the angle of arrival of an incoming signal. These types of systems are often built to account for signals that bounce or reflect off objects in the area of the network.

Knowledge of A and B's distance from each other can be gained through a number of different methods. If A and B knew of each other's locations, they could calculate their distance apart using the following variation of the Pythagorean Theorem

$$d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}. \tag{2.3}$$

However, this does not help to determine the locations of A and B. A viable option uses time of arrival information to obtain relative distance information. This exploits the physical property that electromagnetic signals travel at known velocities; this is used to calculate an object's distance based upon when its signal was sent and consequently received by an anchor node. Time difference of arrival may also be used, but is not seen as frequently, in triangulation as it is in trilateration because of the requirement of a third party. Consider a node broadcasts a signal that is consequently received by three anchor nodes (anchors are nodes for which all information, e.g.,location, is known *a priori* [10]). Suppose the anchor nodes share the times they received the signals, compute the differences, and provide an estimate of the distance to the transmitting node based upon their own locations.

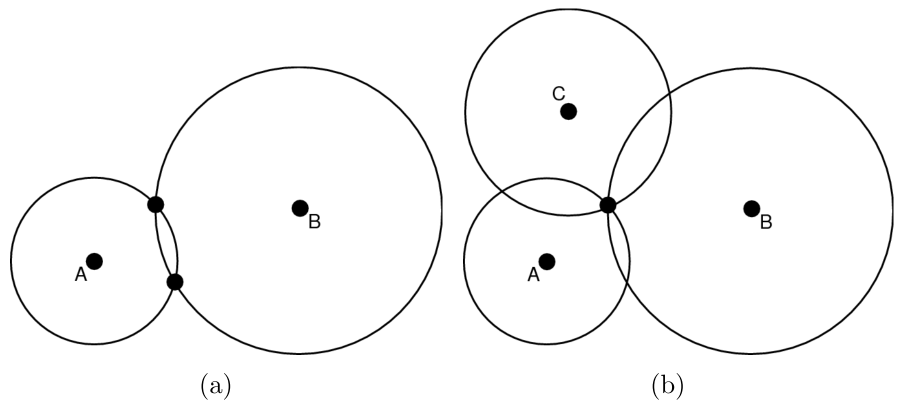


Figure 2.2: (a)Example of trilateration with two anchors.
(b)Example of trilateration with three anchors.

Trilateration is a well-established localization method and uses the distance from which the node to be localized is to each anchor, as opposed to triangulation using angles to calculate node positions. This distance becomes the radius of each anchor node which provides the ability to create a circle around each anchor. Distance information is determined through methods such as signal time of arrival. Incorporating two anchor nodes into a system to localize a third provides the location of the node to be localized but with ambiguity, i.e., the two circles of the anchor nodes will intersect at two points revealing two potential locations of the node to be localized as depicted in Figure 2.2(a). To resolve this ambiguity, the addition of a third anchor node (C) is necessary. The intersection of the three circumferences of the anchor nodes becomes the position of the node to be localized as seen in Figure 2.2(b).

Since this research is to find the location of several nodes, possibly several hops away from an anchor node, position information must be aggregated throughout the network, the process is known as map growing. Three general steps for the map growing process have been proposed by [7]. The first builds an initial map. Here, three nodes are localized and consequently become the "center island" [7]. The process for creating the center island described by [7] is as follows

1. Pick starting node: a node is randomly selected based on its degree (the degree being the number of one-hop connections branching off the selected node). The

degree of the selected node must be greater than or equal to the degree of its immediate neighbors.

2. Select two other nodes to form a triangle such that each of the angles of the triangle are at least 30 degrees, avoiding collinearity, for which triangulation fails.

3. Establish local coordinates for the three selected nodes. One node will be given the origin coordinates (0,0) and a second node will be given coordinates to lay on the x-axis such that it can be defined as (x,0). The location of the third node can then be through simple trigonometry.

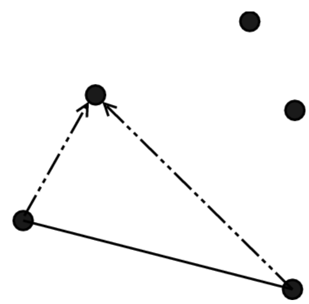


Figure 2.3: Two anchors determining the position of a non-anchor.

Once these three substeps are complete, these nodes effectively become anchor nodes and step-two of the map growing process can begin: growing the map itself. Each anchor node broadcasts its position to its immediate neighbors; when an unlocalized node receives positional information from two anchor nodes, it computes its own location with respect to the anchor nodes. This process repeats until all nodes in the network have been localized, as seen in Figures 2.4 and 2.5.

The final step transforms the relative map to an absolute one, i.e., placing the nodes' coordinates on real locations. All of the nodes discovered in the map have positions known to one another but which are relative to the network. As such, the network may not be useful when only relative positions are known. A transformation is needed in order to reorient the map to absolute positions. To do this, at least three nodes with known absolute positions will be needed [7]. An affine transformation [7]

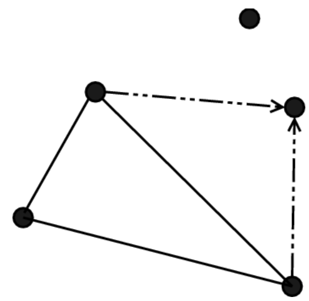


Figure 2.4: Determining the position of a 4^{th} non-anchor.

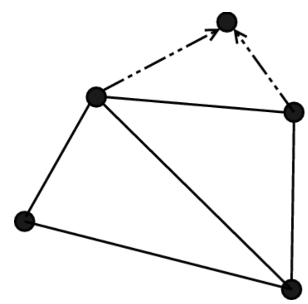


Figure 2.5: Determining the position of a 5^{th} non-anchor.

converts the map from a relative one to an absolute one. When all three of these steps have been completed, the map of the network has been successfully grown.

There is a difference the difference between the map growing previously described and map constraining this research is proposing. Map constraining borrows the idea of iteratively localizing nodes on a map. Yet, instead of discovering locations of new nodes in a map, the application iteratively constrains possible locations in order to reduce location estimates as thoroughly as possible. This iterative process will utilize a brute force approach, exhaustively checking every potential node location. After applying all possible constraints, the node may still have many potential locations at which point the geometric center of mass of these potential locations can be used as the final estimate.

2.3 Sensor Networks

Sensor networks gather information about the surrounding environment by sensing and passing that information to the entity collecting it. Sensor networks have been

the focus of many studies since the early 1980's. Research in this area became more popular in the late 1990's when wireless communications became more commonplace. The scientific community and the Department of Defense saw great value in investing research efforts into wireless sensor networks and momentum to technologically further sensor networks has increased.

Localization is necessary in a sensor network because of the intended use of sensor networks: data collection. Information gathered can range from tracking ground movement, current weather conditions, or short-range communication nodes for users within the network. All of these applications require localization of some form or another. Localizing the network depends greatly on environmental factors, directional and range characteristics of the network devices, localization methods used, and the deployment method, e.g., predetermined locations for each node versus nodes randomly dropped into a location. Nodes randomly dropped into an area will likely be more difficult to localize than nodes placed into predetermined positions. The need to localize nodes in a preselected arrangement may seem unnecessary, however, the network should still have the ability to do so. A node may accidentally (or intentionally) be moved into a new location. When this occurs, the localization routine must determine the new location of the node.

Consider a sensor network deployed into a battle-space to track enemy troop movement in an area of tactical interest. For such an application to be successful each node needs to know location information about itself, which nodes it communicate with, where the locations of those nodes are in relation to the specified node, and where the node itself is located based on a selected coordinate system, e.g., the global coordinate system. If this information in the network is not known, tracking ground movement within the network would be limited to “something in the network is moving”. Without positional estimates of the tracking nodes, troop movement information cannot be derived.

Applications need not be all military in nature, however. Take, for example, a sensor network deployed in a national forest. This network could perform a variety of useful environmental monitoring functions. Movements of certain species of animals, including endangered ones, could be tracked. Catastrophes such as large scale wild fires could be subdued. If a sensor were able to relay information about the start of a fire, response teams would be able to get to the location faster and prevent further spreading. Sensors could be deployed in an environmental area where minimal interaction between humans and the environment is needed (such as the Galapagos Islands) or an area not habitable by humans (such as the ocean floor). Many other applications could be conceived of, all of which would necessitate localization.

2.4 Infrared Communication

Infrared (IR) is an electromagnetic radiation whose wavelength is longer than that of visible light yet shorter than microwaves and radio waves [9]. It was found to be useable for data transmission and consequently developed for wireless communications by a number of different companies in the early 1990's.

In 1993 a number of the companies that developed infrared communications formed the Infrared Data Association (IrDA) to standardize IR communication technology. The first IrDA standard (IrDA 1.0) was published in 1994 and incorporated the following features and characteristics:

- IR uses the same resources as a standard serial port
- It is intended to be a serial cable replacement
- The devices have a typical cone angle of 15-30 degrees
- Maintains a data rate of 2400-115,200 bps

In 1995, a data transmission rate of 4 Mbps was added to the specification. The standard became IrDA 1.1 included the following changes:

- Can be used as a parallel port replacement

- Data rate of 1.152-4 Mbps

The primary objective of IrDA was “to create an interoperable, low-cost infrared data interconnection standard that supports a walk-up, point-to-point user model that is adaptable to a broad range of mobile appliances that need to connect to peripheral devices and hosts” [9]. Once standards had been established, the commercial use of infrared would become much more viable. Thus, infrared became marketable with its primary focus in the professional sector. It was not long until infrared was incorporated into personal digital assistants, laptops, printers, and digital cameras. All of their operations consist of short bursts of data over small distances, e.g., in an office setting. Thus, the devices are not required to be constantly connected, which works well for the media since it requires a line-of-site connection.

Even though the office scenario remains the primary use of infrared technology, entire networks have been based on infrared [2,3,5]. These networks have been largely ad-hoc but have limitations based on the design of the infrared communication device. Because of the physical limitations of the infrared devices, they are only able to communicate with one device at a time. Thus, machines in an infrared ad-hoc network would not be able to broadcast to the entire network; transmissions are relayed between machines when a message is sent to a machine that is not in direct contact with the sender.

Infrared has useful properties not found in radio frequency devices, such as 802.11 and Bluetooth. Both of the aforementioned media are broadcast. Infrared is directional with an IrDA specified device field of view between 15 and 30 degrees. This property can be useful for various reasons, including security. As infrared is line-of-sight, its detectability is limited; while infrared can reflect, to intercept a message, an intruder would have to be somewhere in the line-of-sight area of the two infrared devices. Secondly, this directionality can be exploited to gain positional information. Consider two infrared devices placed on an anchor node; one device facing left and the other facing right. If another object with infrared capabilities passed by the anchor

node and the infrared device on the left-hand side of the anchor node saw the object, but the right-hand infrared device did not, information about the passing object's position is known. Note that the exact location may not be determined, but it is certain the passing object is on the left.

The IrDA standard specifies a fairly low output power making the devices short-range, generally less than 25 feet [1], which limits its detectability. Other properties include low-power consumption and affordability (infrared transceivers are very economical to mass produce because of the manner in which the transmission devices are built: a single light emitting diode (LED) and photodiode are utilized in the transceiver of an infrared device). For research purposes, it can also be used to mimic a highly directional network, such as one that uses laser links, for a fraction of the cost.

2.5 Current Research and Application Areas

Smart Dust [13] can be considered a wireless ad-hoc sensor network on a much smaller scale. The Smart Dust project is developing devices that are approximately one cubic-millimeter in volume. A primary concern with this type of device is energy conservation and this has become the focal point of much of the Smart Dust research. Additionally, because of the small size, the devices have very limited communications.

One method of communication the nodes use through passive light reflection. Nodes have a tiny onboard mirror which reflects light. The mirror can be moved in two different positions; one position represents a 1 (on), and the other position represents a 0 (off). The mirrors switch between the on and off positions at up to 1000 times per second using very little energy; less than a nanojoule per on/off change. However, this passive communication method has some limitations, the primary being that a central station must be the source source of light for node communication. Additionally, the nodes are only able to communicate with the central station, creating latency issues as well as line-of-sight issues. For example, if a node is unable to see the central station it is isolated from the sensor network. Furthermore, the mirrors are so small

they only reflect back a fraction of the incoming light which limits the communication distance.

Because of these limitations nodes must provide their own light source which allows them to communicate without a central station. The nodes incorporate an onboard laser which is reflected off a steering mirror in the direction of the receiver. This makes energy conservation more of a concern compared to the passive node sensors. Nodes must now take additional energy conserving tasks such as comparing communication needs and routing schemes before transmitting. To conserve power, nodes go into a sleep mode. However, this introduces new difficulties. Latency will increase as well as frequent network topology changes.

Sensor networks are also used for habitat monitoring [8] to have as little human impact on the research locations as possible. This is especially important in coastal areas during breeding season where minimal disturbance is crucial to the successful incubation and birth of many wildlife fowl species.

Mica motes developed by University of California, Berkeley, were used in the network. This particular mote uses one RF channel at 916MHz, which can be used for bidirectional communications at up to 40 kbps. Each mote has 512 KB of onboard memory and is powered by two AA batteries. Sensors were added into the motes to detect environmental conditions such as temperature, air pressure, humidity, and wildlife movement.

A number of requirements were thought to be necessary for monitoring. Some include network internet access, enough power for the nodes to run without interference for up to one year, nodes that would be non-intrusive to the island, and the ability to archive data collected. The system has a hierarchical implementation where patches of nodes are deployed and each patch contains up to 100 nodes. Gateways are responsible for forwarding data and information collected by the nodes to a transit network which forwards the data to the base station for collection, examination, and archiving.

Additional localization research using directional antennas has been accomplished through the Computer Engineering Department at The Ohio State University [4]. They propose using only received signal strength from the directional antennas for localization estimates. One approach uses the raw received signal strength measurements for position estimates. The second approach uses the raw measurements to calculate angles of arrival which in turn were used for positional estimates.

Not surprisingly, angle of arrival information was more accurate when the beamwidths of the transmitters were as narrow as possible. Clearly this serves to reduce angle of arrival error. However, the sending and receiving nodes' antennas must be be aligned with greater precision and a single node may not be able to receive signals from multiple nodes simultaneously.

The benefits of directional antennas outweigh the costs when compared to omnidirectional antennas. The performance advantages included lower power consumption, reduced radio interference between nodes, geographical routing, and an increase in the communications range. However, there was an increase in communication protocols complexity due to the directionality and the nature of geographical routing.

Localization and communication efforts for indoor, multi-robot systems is being researched [6]. Robots use infrared communicators to relay information regarding relative positioning. Each robot has twelve infrared communicators; four devices for the front, rear, left and right sides of the robots. Additionally, the robots have four receivers, one for each side of the robots, to receive RF transmissions and calculate relative distance and angle of arrival for the RF signals.

The system determined ranging information using received signal strength. Accuracy of the system is limited by the hardware and dependent on three separate factors: the received signal strength indications versus the actual distance between robots, minute differences in the optical hardware, and misalignments between the receptors and transmitters of each robot. With these limitations, the robots achieved

a communication range of up to three meters with accuracy within 40cm. Some of the following issues in the system were noted:

- The number of robots in the system was assumed to be known a priori
- Intervals between transmissions were fixed which did not allow for optimized throughput in the system
- The area that the robots interacted with was fixed which did not allow for dynamic environment testing

A hybrid infrared/radio frequency system [11] can be used indoors where topological features differ from outdoor environments. A hybrid system of infrared and radio frequency can use GPS for local (indoor) environments [11]. Costs are reduced through the abundant availability and low production costs of infrared and radio frequency devices. Additionally, the system is highly flexible, allowing users to tailor the systems towards their needs based on their current location infrastructures.

2.6 Summary

Triangulation is useful in cases where interfaces are highly directional or line of sight is exact. While infrared is not highly directional, it has enough directionality such that certain aspects of triangulation are useful. Even though trilateration is traditionally used in conjunction with broadcast media, its properties are useful for localization with infrared; the most useful property being the intersection of the device's communication ranges. Once initial positions of devices in the network are known, all of the nodes can be localized. Sensor network localization was discussed. Once the sensor network has been localized, abundant applications of the network can be provided. Current research in sensor network was also provided.

III. Methodology

3.1 Overview

This chapter discusses in detail the directional communication localization problem. Additionally, expectations of localization results are discussed, as well as the brute force algorithmic approach used to solve this problem. Setup of the experiments are also discussed with the inclusion of any assumptions made during the research.

3.2 Problem Definition

The relative positions of nodes in a sensor network is often required for particular tasks. While positioning information can be obtained through dedicated positioning systems, e.g, Global Positioning System (GPS) receivers, it is preferable to have the positioning information derived from the network itself; this process is called localization. In this research, localization is investigated under weak conditions using directional transceivers on the communicating devices. Feasibility of localization using the directional transceivers is investigated through simulation.

3.2.1 Definition of Terms. $Maps$ represent constraints on the possible locations a given node could be and the possible orientations a node could take on that particular location. Simple transceivers do not estimate an angle of arrival, nor a signal strength which can be exploited for localization. Instead, these transceivers are simply communication devices which happen to have a minimum and maximum range as well as a useable field of view called a beam. Combining the beam along with the minimum and maximum communication range an area is called a $frustum$, which is loosely equivalent to the notion of a frustum used in computer graphics. For communication to exist, two transceivers must be positioned within each others $frustums$. Consider Figure 3.1. A and B are within each others' $frustums$, therefore communication is possible.

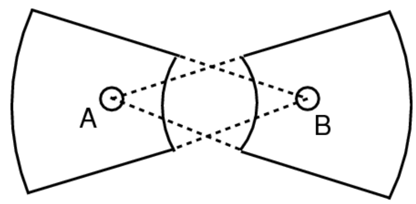


Figure 3.1: A and B within each others' *frustums*

In Figure 3.2, B is within communication range of A. However, it is not within A's *frustum*, hence the two are unable to communicate.

In the absence of positional or orientation constraints on B, its potential locations include the entire span of the search-space in question. If A and B are communicating, however, there are known constraints on the possible position of B; namely B must be within the *frustum* of A. This information is stored in what is called a Map of Potential Locations (MPL). If it is known B is communicating with another node, perhaps though a different transceiver, B's MPL can be refined.

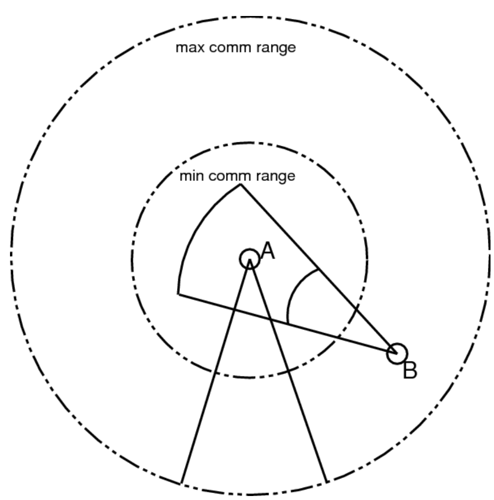
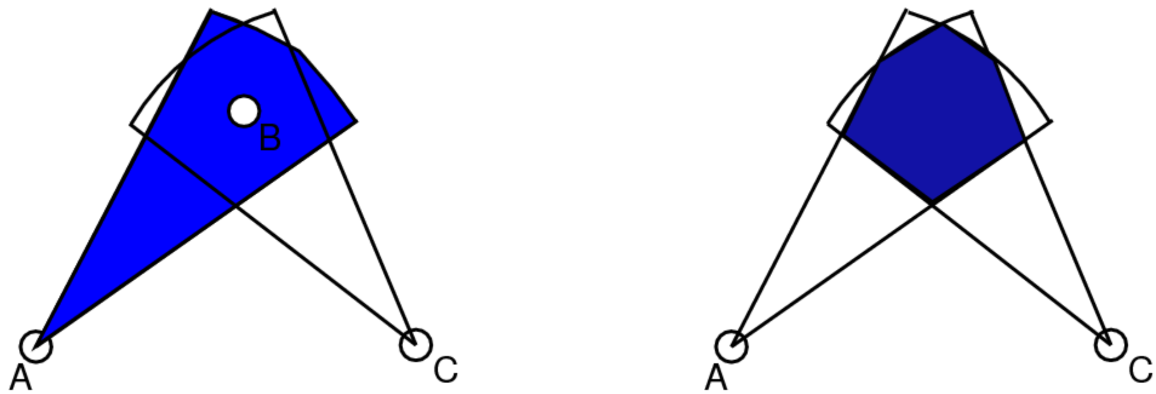


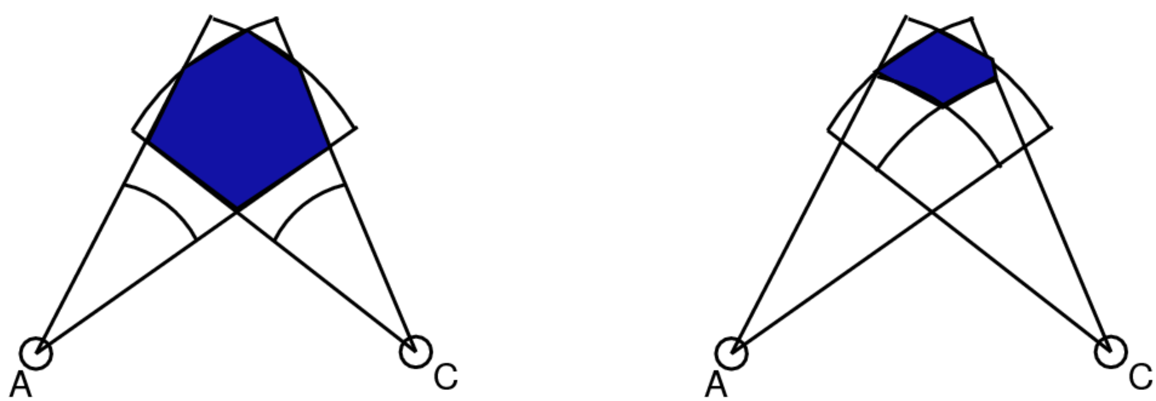
Figure 3.2: B within range of A, but not within A's beam



(a) (b)

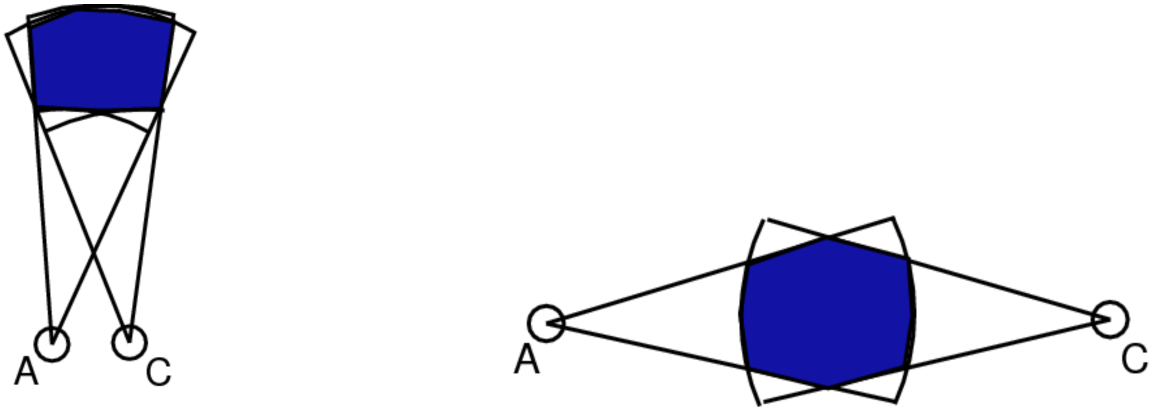
Figure 3.3: (a)Node B within communication range of A and C.
(b)The intersection of A and C for B's potential locations.

3.2.2 MPL Refinement Through Intersection. Assume a third node C is introduced and is communicating with B, shown in Figure 3.3(a). The MPL for B refined by A includes the entire beam of A. Adding the constraint of C further refines the MPL of B represented here by the intersection of the beams of A and C in Figure 3.3(b).



(a) (b)

Figure 3.4: (a)B's potential locations with a large difference in A and C's min-max range.
(b) B's potential locations with a small difference in A and C's min-max range.



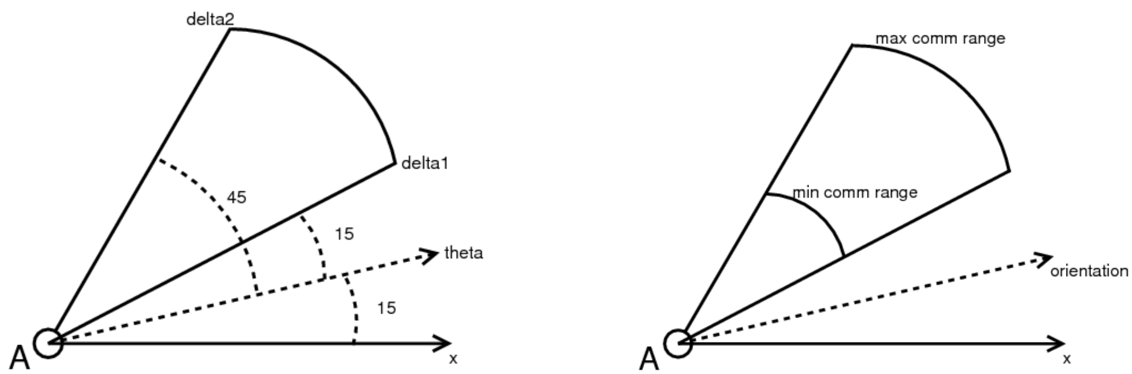
(a) (b)

Figure 3.5: (a) Potential locations of B given close positioning of A and C. (b) Potential locations of B with A and C facing each other.

3.2.3 Effect of Tight Range Bounds on MPL. The minimum communication range is assumed to be known (and could be zero) in addition to a known maximum range. Using a min-max communication range setup, it is possible to further refine the Map of Potential Locations (MPL) of B. The amount of refinement depends on the min-max range difference.

Take for example two different scenarios for nodes A, B, and C. The first scenario assumes a large difference in the min-max communication range of A and C in Figure 3.4(a). Because the minimum range is is outside of the intersection range, having a large min-max range difference in certain specific cases is not useful. Now, assume a scenario with a small difference in the communication range of A and C in Figure 3.4(b). The area of B's potential locations has been reduced further from Figure 3.3(b). If the minimum communication range is used by all nodes in the network approaches the maximum communication range, the MPL of B would be reduced to a single point. This is equivalent to trilateration.

3.2.4 Degenerate Refinements. In some cases, knowledge of additional communication may not contribute to the refinement of the MPL for a node. For example, Figure 3.4 are general case scenarios. The locations of A and C could vary greatly and are not always so well structured. Take for example the scenario in which A and



(a) (b)

Figure 3.6: (a) Node A with an orientation of 15 degrees and relative transceiver angles of 15 and 45 degrees.
(b) Node A with minimum and maximum communication ranges.

C are almost next to each other in Figure 3.5(a). In this case, the ranging information is somewhat useful, but the potential locations of B are not reduced very much in the intersection of A and C. Also consider an additional scenario in which the beams of A and C's transceivers face each other in Figure 3.5(b). This scenario, too, does not provide significant location refinement. Therefore, node locations and min-max range differences play a very important role in the directional communication localization process.

3.2.5 Orientation Constrainment. One of the key contributions to localization in this research is done through what is defined as *orientation constrainment*. Each node is assumed to have a given orientation relative to a predetermined reference angle, in this case the positive x-axis. For every directional transceiver on the nodes, a relative offset from the orientation of the node is known for each transceiver. Consider node A with an orientation of 15 degrees. The relative angles of the transceiver are 15 degrees and 45 degrees. The resulting *frustum* is shown in Figure 3.6.

For all nodes, the transceiver angles relative to their orientations are assumed to be known and are called Relative Transceiver Angles (RTA). Hence, a range of orientations of B can be determined for each position within A's frustum. In Figure 3.7(a),

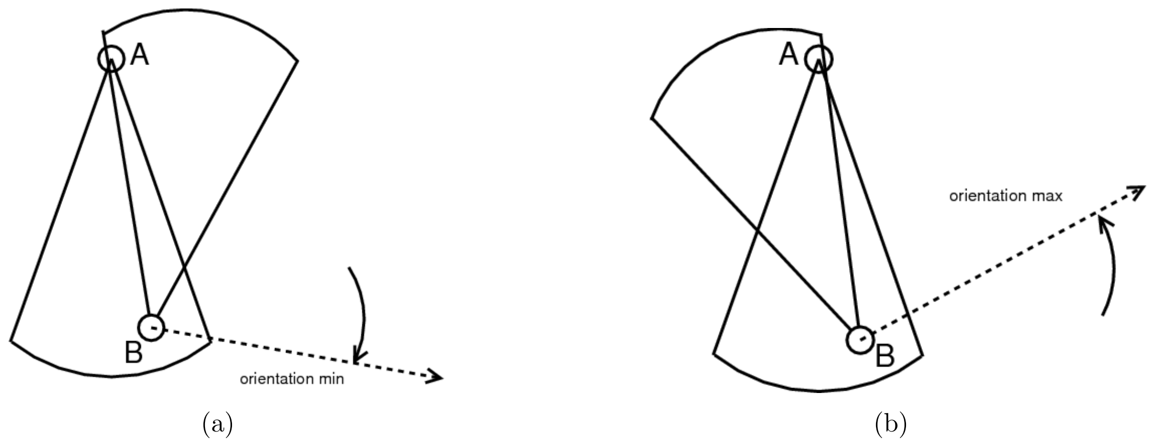


Figure 3.7: (a) B's minimum orientation constrained through A.
(b) B's maximum orientation constrained through A.

a location for B has been selected and the minimum orientation can be found. B can now be rotated to the opposite extreme to find the maximum orientation as shown in Figure 3.7(b). B remains in the same location, but has been rotated for a maximum orientation while still maintaining communication.

Once A and B are known to be communicating, B's potential relative locations and orientations for each location can be calculated. Factors that influence the potential locations of B include A's possible locations, A's minimum and maximum communication ranges, the beamwidth of A's transceiver as well as B's potential orientations. B's minimum and maximum communication ranges are influenced by A's potential locations and B's transceiver beamwidth.

New information is now available in addition to B's MPL, orientation information is added. The combination of location and orientation constraints in the MPL is defined as a Map of Potential Locations and Orientation (MPLO).

If the minimum and maximum orientations for B are combined, the range can be described by Figure 3.8. This orientation information is not useful though, until a third node, for example C, can communicate with B as shown in Figure 3.9.

In Figure 3.9(a), after establishing communication with both A and C, B has been rotated clockwise until it reaches a limit in which it can still communicate with

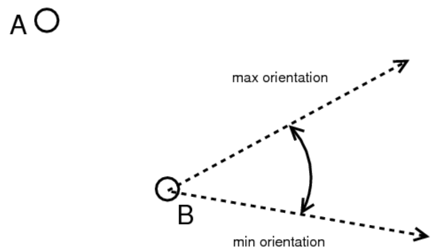
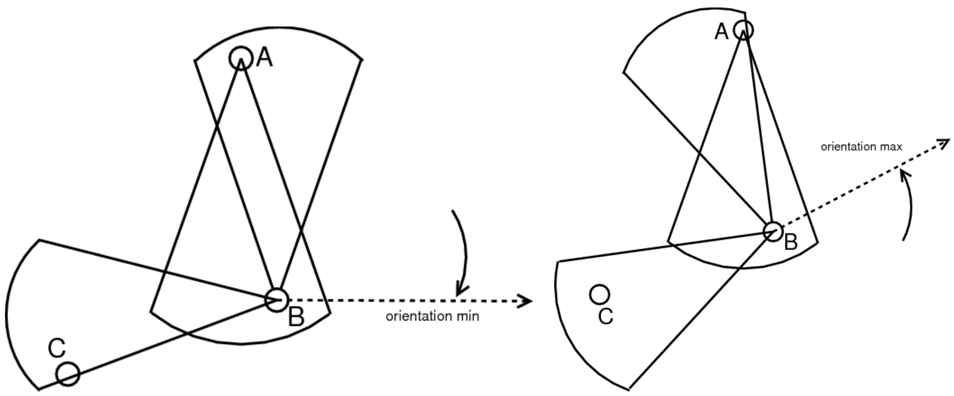


Figure 3.8: B's subsequent minimum and maximum orientation range.



(a) (b)

Figure 3.9: (a) B's minimum orientation consequently constrained through C. (b) B's maximum orientation remains constrained through A.

A and C. Any further clockwise rotation will break the communication with C. Note that B could rotate clockwise several degrees before breaking communication with A. Hence the introduction of an additional constraint, namely communication with C, has decreased the range of the orientation (from Figure 3.7(a)) in which simultaneous communication is maintained in this particular potential location. If B is rotated counterclockwise until just before communication with one node is lost, in this case A, the maximum orientation is limited by A as shown in Figure 3.9(b).

The maximum orientation remains unchanged from the previous calculation and there is now a new, reduced, min-max orientation represented in Figure 3.10.

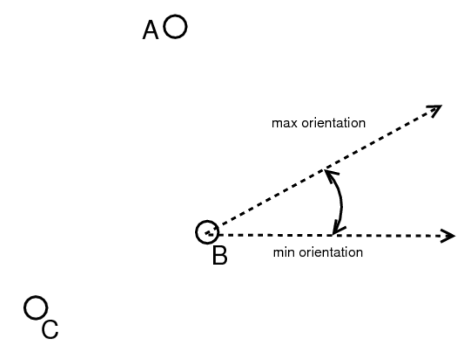


Figure 3.10: B's newly constrained minimum-maximum orientation

3.2.6 Convolution. Ignoring orientation constraints would allow the use of convolution to determine the MPL of various nodes. Consider a set of locations for a node A in communication with node B. For simplicity, let each location have a single known orientation. Thus, A's MPL would be represented by the square in Figure 3.11(a). If the MPL for B is refined by A, which may exist anywhere within A's MPL, then the MPL of B must include all possible combinations of A's $frustum$ at any of A's MPL positions (Figure 3.11(b)). This is equivalent to taking the convolution of the $frustum$ and MPL of A, represented by Figure 3.11(c).

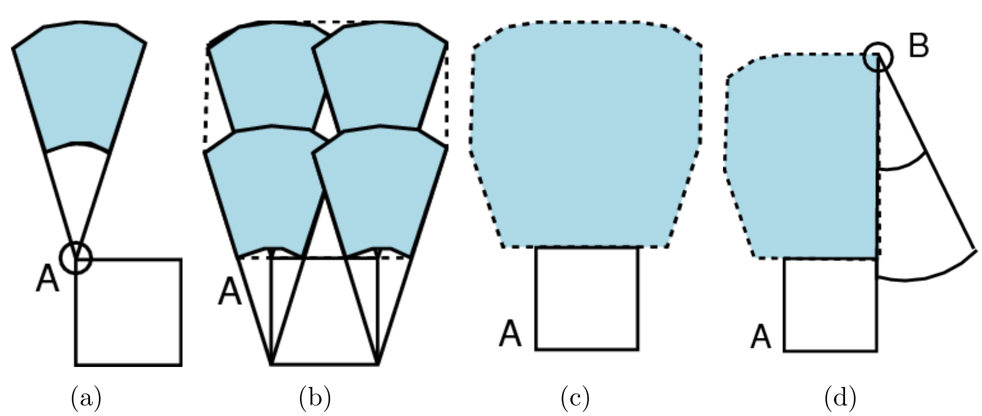


Figure 3.11: (a) Initial location for A to calculate B, (b) B calculated from four positions of A, (c) Shape of B's MPL via convolution, (d) Shape of B's MPL given orientation constrains on B.

The notion of convolution, however, since there are orientation constraints in the problem and they contain much of the solution information. If B's orientation was constrained much like A's, then locations returned by convolution would not be feasible. This is shown in Figure 3.11(d).

3.3 Goals and Hypothesis

Using the concepts presented in the problem definition, it is hypothesized that localization, via methods previously defined, can be done successfully in a multi-node scenario through iterative refinement. If MPLO's of nodes in a given topology are refined iteratively through previously refined nodes in the network, additional information could be gained in the MPLO's of those nodes. This research will show that localization via range limited directional communication is feasible. The system should be able to localize itself using only a small amount of *a priori* information and a few assumptions.

3.4 Applying Position and Orientation Constraints for Localization

3.4.1 Iterative Refinement. Because multiple communicating nodes are in a network, each impose various constraints on the possible locations of various nodes. Thus there must be a way to iteratively refine the possible locations of nodes. MPLO provides a vehicle to do this. To iterate a refinement, one node is chosen as a constrainer, and another node is chose to be refined. The MPLO of the constrainer serves to potentially limit the MPLO of the node to be refined.

3.4.2 Effect of Orientation Constraints on Possible Locations. Consider the scenario in Figure 3.12. Assume A and C are facing each other, in known positions and orientations, and have a beamwidth of 100 degrees. Assume that B has transceivers available to talk to A and C.

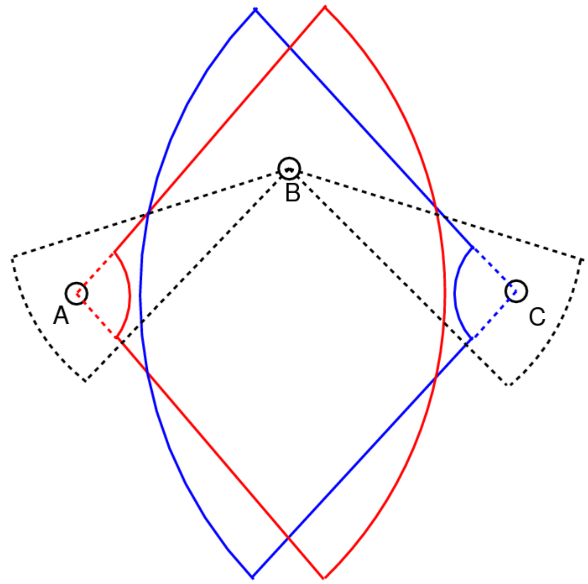


Figure 3.12: B communicating with A and C

When B and A communicate, B's MPL is the entire area of A's *frustum* depicted in Figure 3.13. Because B is also communicating with C, the MPL of B can be refined by C, as shown in Figures 3.14 and 3.15. Assuming no knowledge of B's Relative Transceiver Angles (RTA's), the only additional information attainable is that B's potential locations could be anywhere inside the intersection of A and C's communication areas. This intersection does not refine B's potential locations significantly as can be seen by comparing Figures 3.14 and 3.15.

If B's RTA's are known, however, constraints upon its orientation can be calculated. Potential locations of B can be reduced, represented in green, by Figure 3.16. This is a significant reduction of potential locations and is useful even when A and C have loose communication constraints.

Note that the lower curve of the green area represents the constraints by the upper edges of the RTA's. The upper curve, of which only a small portion is visible, is a result of the lower edges of the RTA's. If it was not known which transceiver was communicating with which node, there would be a symmetric green area in the bottom half of Figure 3.16 as well.

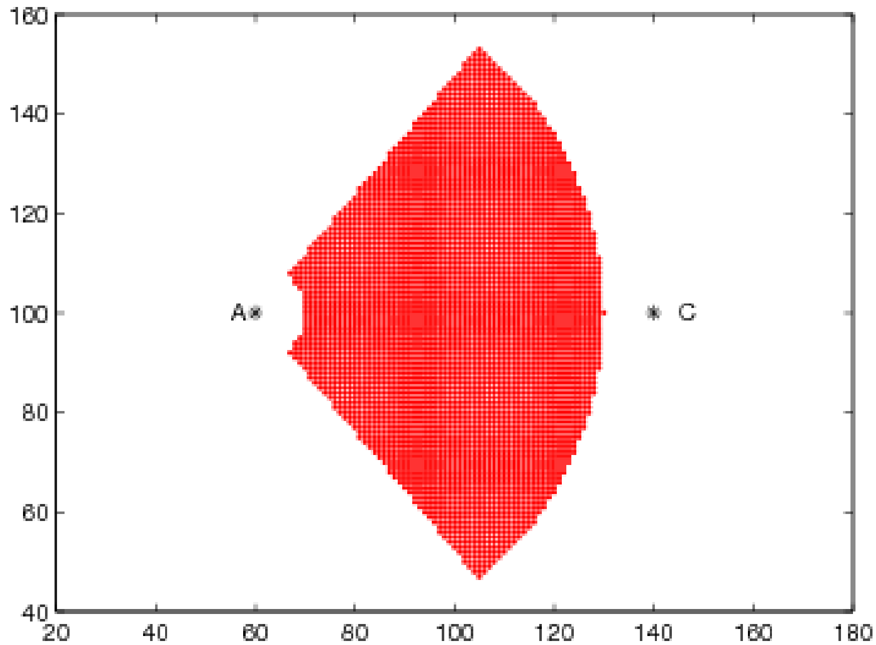


Figure 3.13: All potential locations of B seen through A's transceiver

3.5 Algorithmic Approach Through Iterative Refinement

Assume three nodes A, B, and C are placed in such a fashion that node B can communicate with A and C at the same time, i.e., it has two directional transceivers. A and C anchors and B's location is unknown. Each node starts with a MPLO. The MPLO is represented as a bitmap and for each location in the map, with a 1 signifying that this node may be in that location, while a 0 signifies this node is not in that location. Because A and C are anchors, only one location is represented in each of their MPLO's. This location is represented in the bitmap as a 1 and the remaining locations in the MPLO's are designated as 0. As there is no initial information regarding the location of B, it could be anywhere in its MPLO. Hence, B's initial MPLO is all 1's.

The algorithm searches through a grid-space to determine potential locations of B. At each point in the grid, the distance between A and the potential B location is

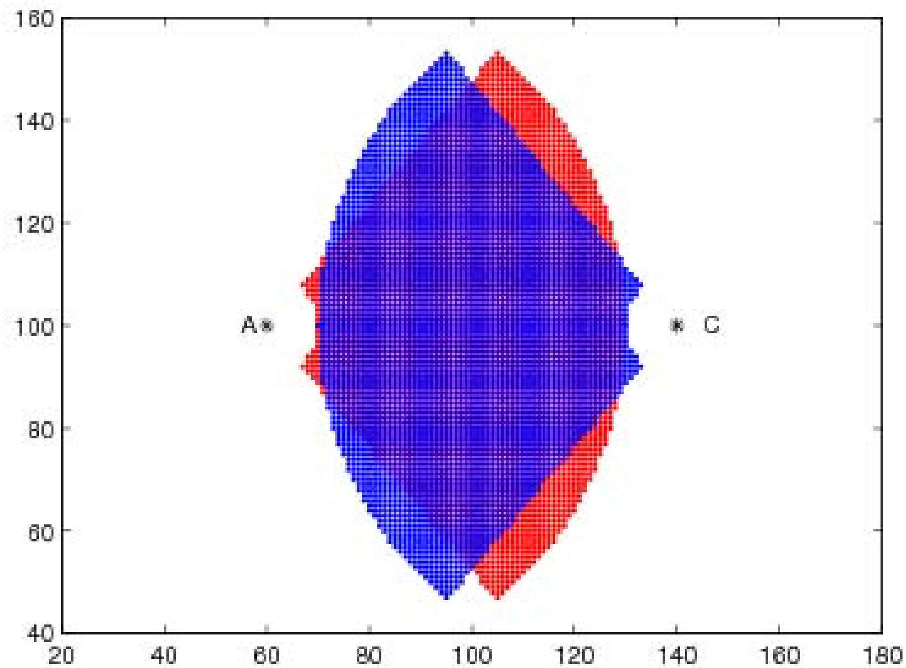


Figure 3.14: All potential locations of B seen through A's transceiver overlapped with C's tranceiver.

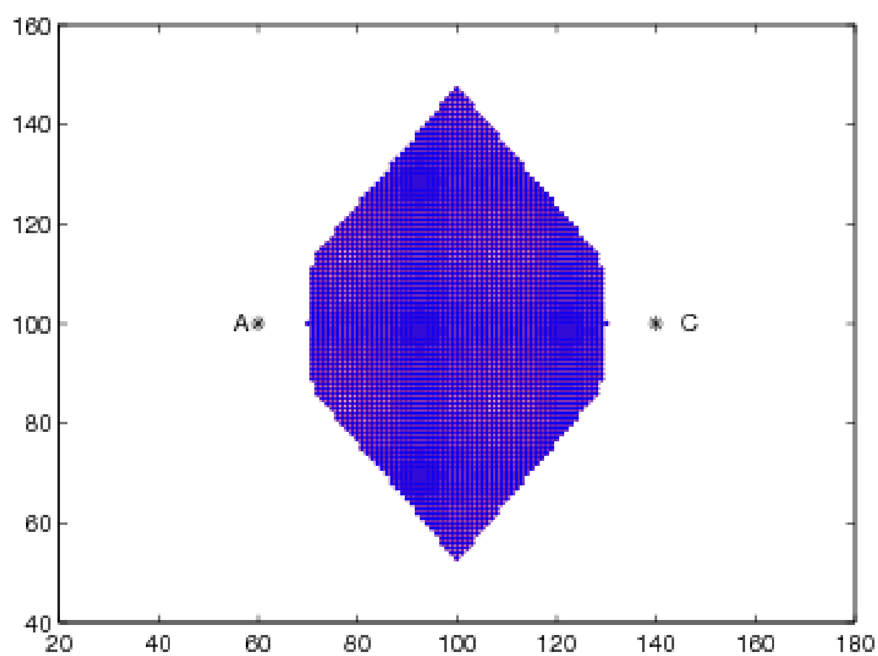


Figure 3.15: Intersection of A and C's refinement of B.

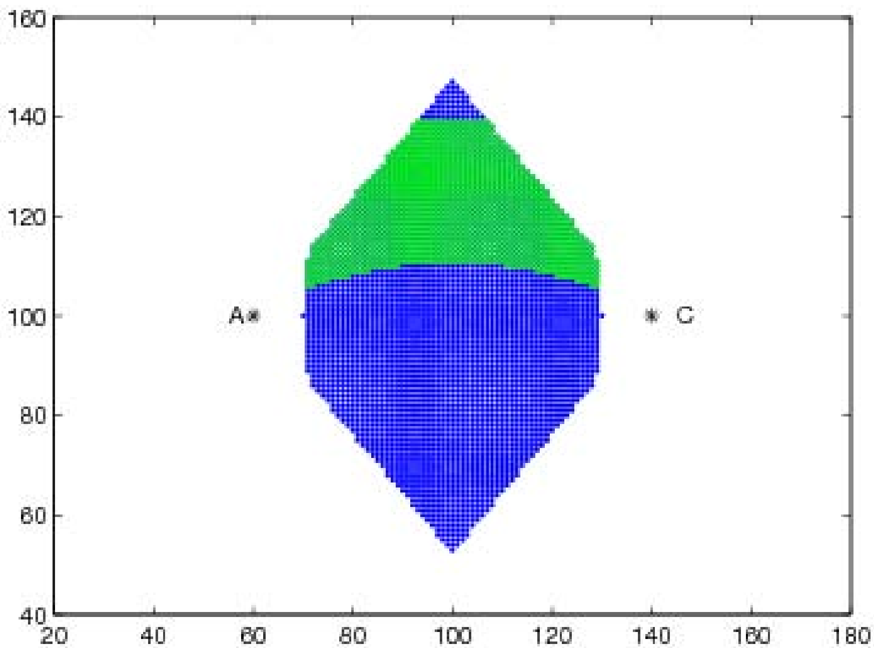


Figure 3.16: Refined locations for B given constraints on its orientation.

calculated using

$$d^2 = (x_2 - x_1)^2 + (y_2 - y_1)^2. \tag{3.1}$$

Using the square of d avoids the costly step of calculating a square root.

If the potential location is not within the min-max range of A, the algorithm sets the bitmap value to 0 and steps to the next potential location for B. If the potential B location is within A's min-max range, as well as A being within B's min-max range, the algorithm determines if the location is inside or outside of A's $frustum$. If B is inside of the $frustum$, a 1 is set in B's MPLO, otherwise a 0 is set in that location. If B is indeed in the $frustum$ of A, the algorithm proceeds to calculate an orientation range for B. Once the entire MPLO for B communicating with A has been calculated, this MPLO is saved as the first refinement of B. Potential locations for B communicating with C can now proceed.

There is now new information that can be used to determine B's location according to C. B's MPLO has been refined by A. Hence, while the algorithm searches through the grid for new potential locations that B could be in while communicating with C, the MPLO refined by A is used. If B is in a location within C's *frustum*, it checks B's current MPLO; if a 0 is in that location the algorithm will not mark that location as a potential for B since it did not exist for A. If there is a 1 in that location, the algorithm will calculate B's potential min-max orientations according to C. These orientations are compared to the orientations stored in B's MPLO from the refinement of A.

If the two orientations coincide, the algorithm maintains a 1 in the location and calculates a new min-max orientation based on a calculation of the old min-max range and the newly found min-max range. The new min-max orientation is stored in B's MPLO if the position is feasible. If, however, the two orientation ranges do not overlap, the currently considered location of B is to a 0. Once the algorithm has completed searching through all locations of B and has refined them according to C, the new MPLO calculated for B is saved.

3.6 Localization Process

Because of the large number of computations required to run this algorithm the order of refinements is important. While an automated task to perform this function is desirable, this feature was not implemented. Instead, for each scenario, a script was written to define the order of node refinements. Refinement begins with the anchor nodes and the nodes they are able to communicate with called one-hop nodes. Once the one-hop nodes have been refined, they refine the nodes that are directly communicating with them called two-hop nodes (as they are two hops away from an anchor). In some cases, the nodes communicating with the one-hop nodes may already be one-hope nodes, otherwise, in general, the two-hop nodes are next to be refined. The two-hop nodes then localize the three-hop nodes. In this fashion, the entire set of MPLO's is refined.

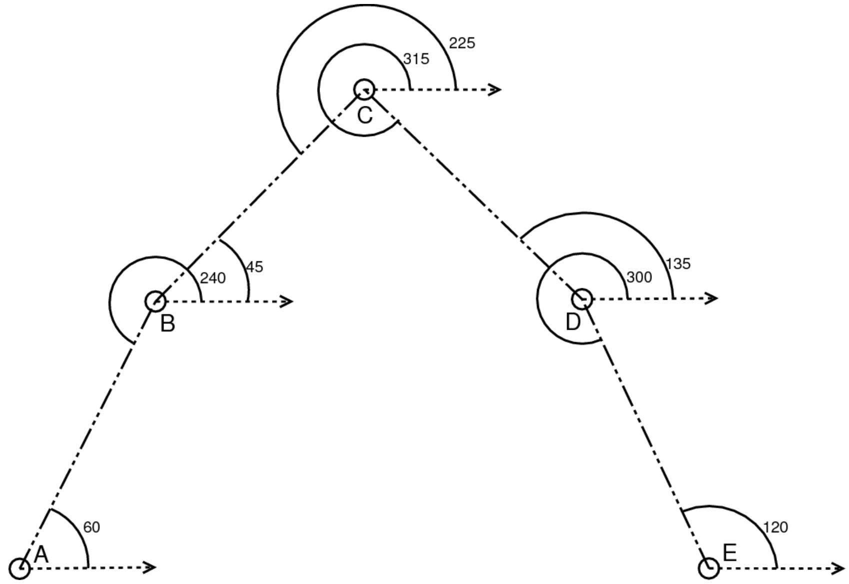


Figure 3.17: Network topology for the 5 node scenario.

Because of a large degree of uncertainty, the MPLO for a three-hop node is not useful for constraining the locations of other nodes. Eventually the effectiveness of refinement tapers off.

3.7 Five Node Scenario

Using the previously mentioned localization methods, a general five node scenario can be localized in a relatively efficient manner. Assume five nodes, A, B, C, D, and E, are arranged as in Figure 3.17.

Nodes A and E are anchors. The information known about nodes B, C, and D is the same as nodes A and E except for locations and orientations.

Nodes B and D are refined first which results in the MPL's in Figure 3.18. Note the algorithm has also determined potential orientations at each point in the MPL's. Once B and D have been refined by A and E, the MPLO for node C can be calculated. C will first be refined by B, which provides locations (in blue) in Figure 3.19. Consequently, D will refine C, and the new locations (in red) are represented in Figure 3.19.

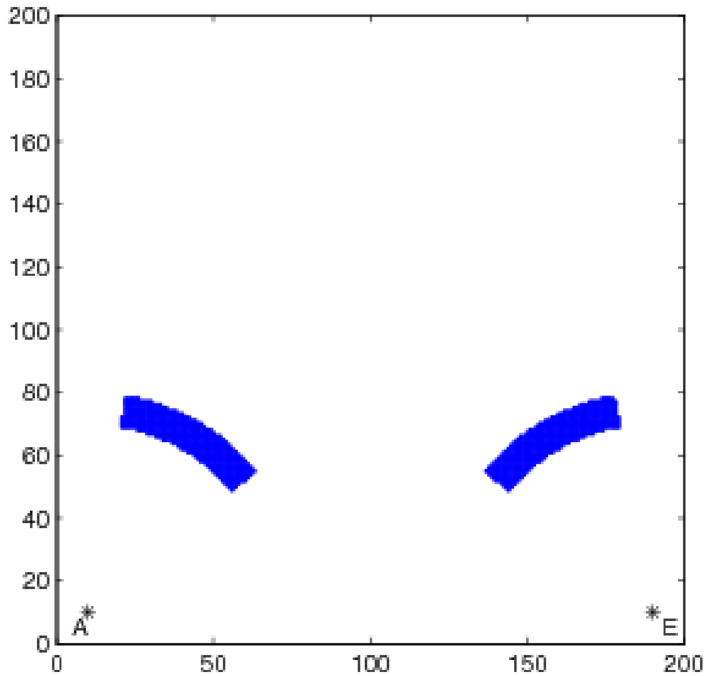


Figure 3.18: Initial refinements of B and D through the anchors.

Once C has been refined by B and D, it can now become a constrainer to refine a new iteration of B and D, which refinements are shown in red in Figure 3.20. The process of re-refining B, C, and D by each other can continue to run indefinitely, but eventually a state will be reached where little to no refinement will be gained. At this point, the graph has been completely refined. In the case of the scenario given, meaningful results diminish after B and D have been refined once by C. Thus, the results provided in Figure 3.20 are complete.

3.8 Carrying Over to a Larger Scenario

Using the techniques from the five-node scenario, it is hypothesized the same can be done for a larger scale network. Results similar to the five node scenario are expected, refinement results may vary. Factors such as anchor positions, node orientations, communication ranges, and topology will impact the precision of the localization results. Particular items of interest which require additional attention

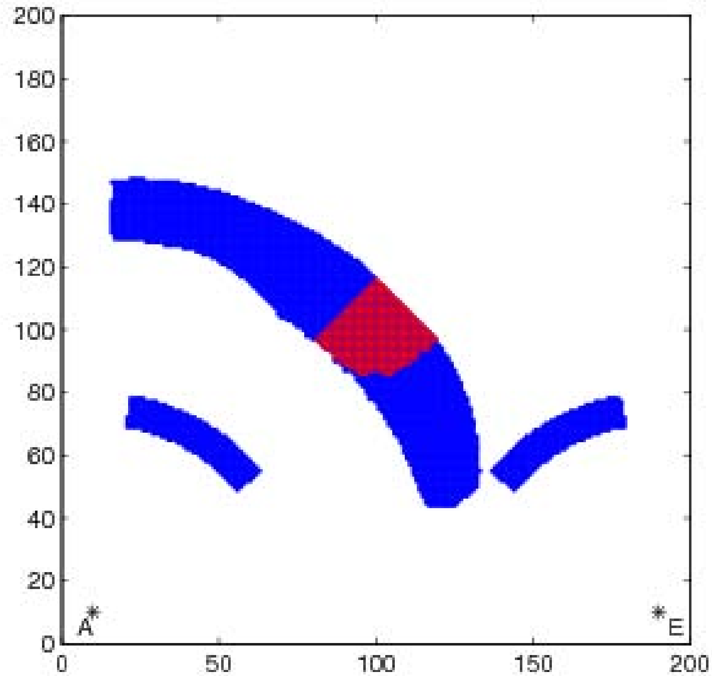


Figure 3.19: Potential locations for C, calculated through B and refined by D.

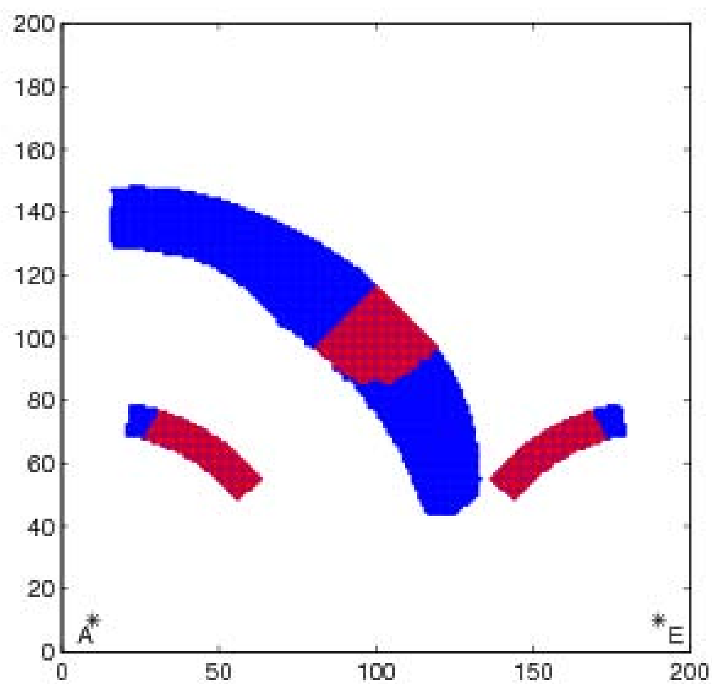


Figure 3.20: Refinements of B and D using the recently refined C.

are the settings of the RTA's as well as the refinement order of nodes in the network. Without a well selected refinement order, refinements have the potential to significantly increase run-time.

3.9 Scenario Parameters

Two larger scale scenarios are considered, each with three of its own experiments. Scenario #1 considers 20 nodes in a fully connected network. The option of including an additional node to act as a communication hub is also considered in the experiment. The position, orientation, RTA's, and beamwidths of the two anchor nodes are known. Beamwidths are fixed at 30 degrees. The remaining node are unknown, i.e., their MPLO's are filled with all 1's, and orientations that are not known but the range of each transceiver and an RTA reference relative to the orientation for each transceiver is. Some experiments include a hub in expectation that the hub will allow advanced refinement of nodes connected to it. The hub includes up to five transceivers which requires additional transceivers on the nodes the hub is in communication with. These additional transceivers also have a beamwidth of 30 degrees.

Scenario #2 is similar to #1 except there are fewer nodes in the network. The topology considerers 14 nodes in a fully connected network. As is the case with Scenario #1, #2 also incorporates an additional hub for further network refinements. With fewer nodes, and more carefully selected RTA's, it is expected that more significant refinement will be seen compared to Scenario #1.

3.10 Summary

In this chapter the localization process was defined. Node communication range and orientation constraints were discussed. The iterative approach of the algorithm used in the experiments was also explained. Refinements to possible node locations using communication range and orientation information was also introduced. Refinement results of small networks and the scenarios used in the experiments were outlined.

IV. Analysis and Results

4.1 Chapter Overview

In this chapter, the results of various experiments are discussed. Analysis is offered for various node configurations and their refinements. Additional insight on why certain experiments achieved better localization results than others is provided.

4.2 Scenario #1

Scenario #1 consists of 20 nodes, in a 200 x 200 grid, in a connected graph as shown in Figure 4.1. Three separate experiments were conducted.

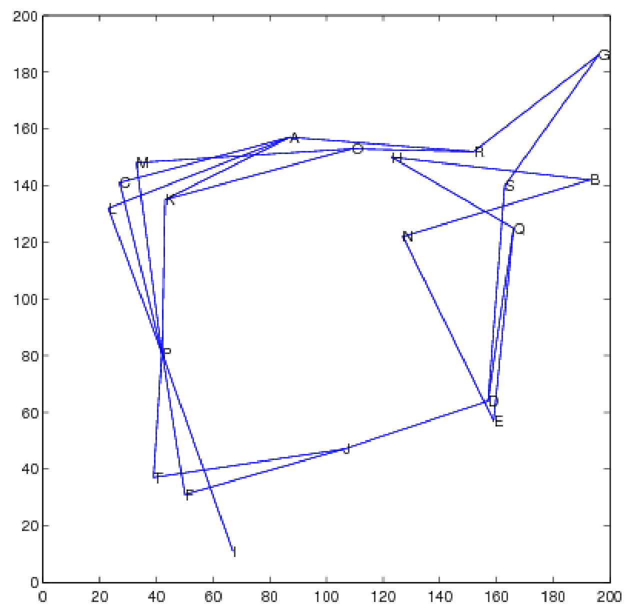


Figure 4.1: Experiment #1-1 topology

- In Experiment #1-1, each node has a unique min-max communication range.
- In Experiment #1-2, a hub node is introduced to the network and every node is assigned a common communication range from 40-80.
- In Experiment #1-3 the hub node remains and each node has a unique min-max communication range.

The locations and orientations of anchor nodes P and Q are known. The RTA's of the communicators are known with each node having two communicators (save for the cases where a hub node is introduced) and a beamwidth of 30 degrees for each communicator. A data file for each node is created at the start of the experiment consisting of the node's unrefined MPLO, which is progressively refined throughout the experiment.

4.2.1 Experiment #1-1. Figure 4.1 is the topology. In this experiment nodes P and Q are anchor nodes at locations (42,81) and (166,25) respectively. The orientations for each anchor is between 355 and 5 degrees. The nodes in this experiment have RTA's and min-max communication range information represented in Table 4.1.

Table 4.1: Nodes with their respective communicator boresights and ranges for Experiment #1-1.

Node	Comm 1	Comm 2	Min Range	Max Range
A	205	355	45	70
B	87	182	60	80
C	13	283	60	80
D	88	201	50	80
E	86	119	60	80
F	19	95	40	60
G	225	286	40	60
H	330	350	45	75
I	115	256	70	80
J	22	195	50	70
K	15	268	50	70
L	20	285	50	70
M	3	275	60	80
N	26	300	65	85
O	190	359	40	80
P	103	275	40	80
Q	149	264	45	70
R	41	180	40	70
S	42	267	50	80
T	11	88	40	70

Figure 4.2 is the resulting MPL from the first refinement of all nodes one hop away from the anchors. Although an anchor may see multiple one-hop nodes per communicator, the refined MPL may be identical for each one-hop node in that communicator's view. The minimum and maximum orientations for each location vary (but only slightly). For example, the MPL of nodes L, C, M, and K, are represented as a single area because they are all similarly constrained. Further refinement may reduce the MPL of a particular node.

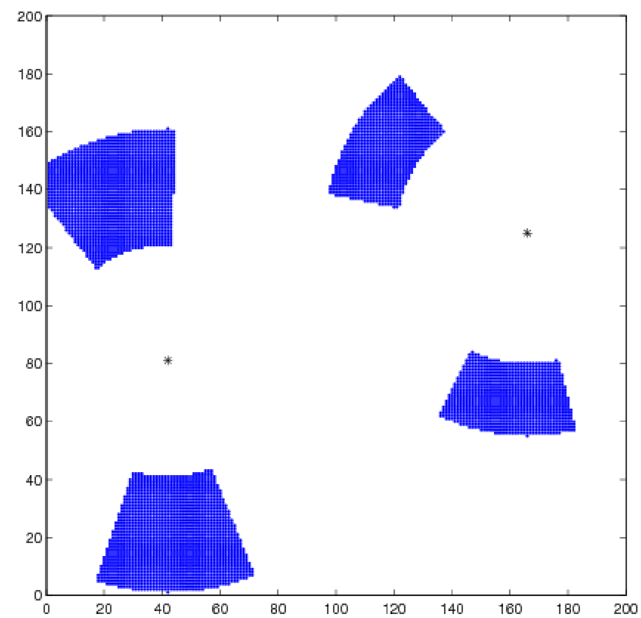


Figure 4.2: MPL for one-hop nodes

Figure 4.3 shows the refinement of node J. The red area denotes the refinement via node T, the green area denotes the refinement via node D, and and the blue area denotes the refinement via node F. The most dramatic refinement of J takes place between T and D whereas the refinement from D to F is not nearly as strong. This is due to the min-max difference in the ranges of T and D, as well as T and D's MPLO's. Node F causes some additional refinement, but is not dramatic as F's locations in its MPLO are the same as those calculated in T's MPLO. Thus, having multiple one-hop nodes communicating through the same transceiver as their constrainer, such as T

and F, will not yield a better refinement. The two one-hop nodes can be treated as a combined one-hop node.

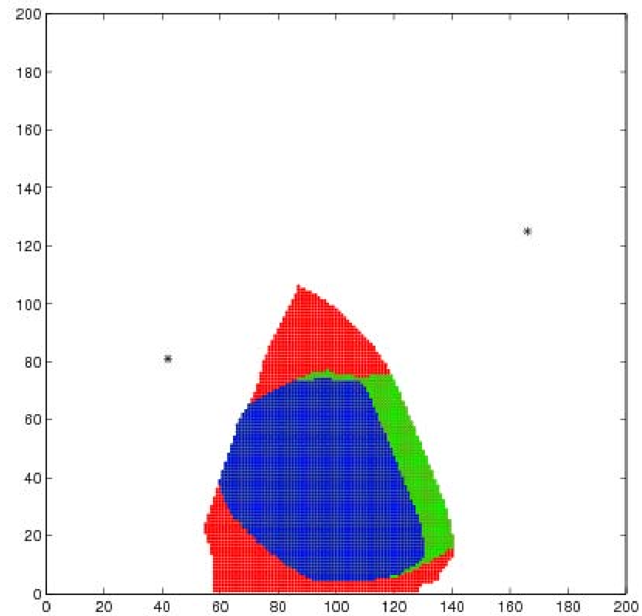


Figure 4.3: Node J through three steps of iterative refinement in Experiment #1-1

Some comment on the unique shapes of J is appropriate. Irregular shapes arise out of various constraints placed upon the network. J was refined by T, D and F. While their $frustums$ are symmetric, the uncertainty of the origin (the $frustum$ coupled with orientations constraints) creates shapes which are not necessarily intuitive.

4.2.2 Experiment #1-2 and #1-3. The network topology for Experiments #1-2 and #1-3 are shown in Figure 4.4. Experiment #1-2 uses a communication range of 40 to 80 for all nodes and Experiment #1-3 uses the ranges specified by Table 4.1. Both experiments use the RTA's noted in Table 4.1. With the addition of a hub, the extra connections and orientations required are noted in Table 4.2.

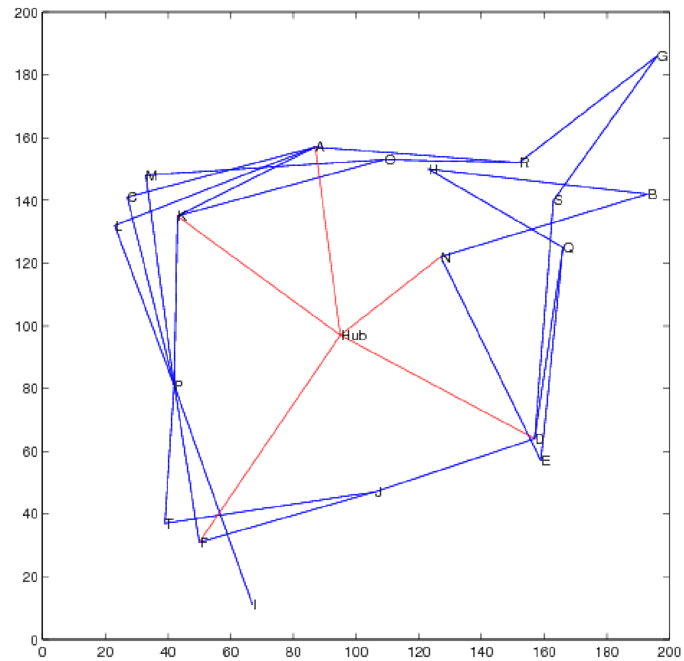


Figure 4.4: Topology for Experiments #1-2 and #1-3

Consider a hub node with connections to five other nodes. For both experiments (one not ranged and one ranged) the hub is refined by node F (red), then node K (green), and finally node D (blue).

The resulting hub refinement without specific range information is in Figure 4.5 and the hub refinement with range information is in Figure 4.6.

Table 4.2: Augmented node transceiver angles and ranges.

Node	Comm 1	Comm 2	Comm 3	Comm 4	Comm 5	Min Range	Max Range
A	205	355	270	-	-	45	75
D	88	201	152	-	-	50	80
F	19	95	57	-	-	40	80
K	15	268	316	-	-	50	70
N	26	300	212	-	-	40	80
Hub	30	91	137	238	331	40	80

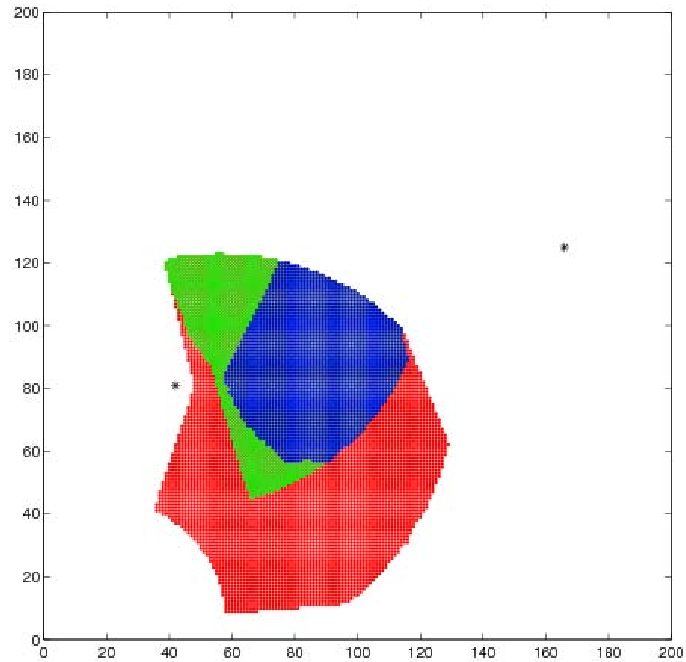


Figure 4.5: Refinement of the hub in Experiment #1-2

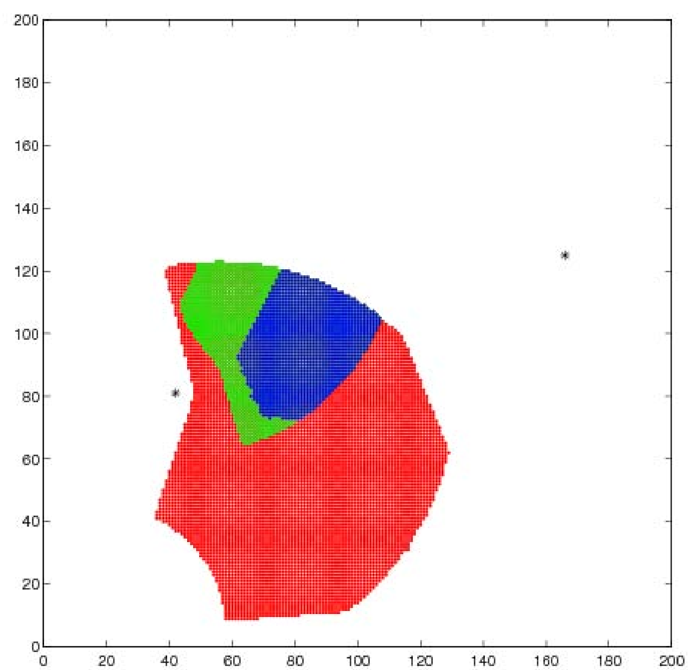


Figure 4.6: Refinement of the hub in Experiment #1-2

Between Figures 4.5 and 4.6, there is no location difference in the first hub refinement by F (the red marked locations) because in both Experiments #1-2 and #1-3, the hub and node F share a communication range from 40 to 80. That is, there is no difference in range so there will be no difference in results. The second and third refinements though, have a noticeable change in the locations calculate. The experiment with ranged information is able to refine the hub's locations more thoroughly than the experiment without ranged information. One feature to note is the hub was refined in its second and third iterations by a fairly large amount in Figures 4.5 and 4.6 because of the fact that the three nodes that refined the hub were all one-hop nodes. Thus, the reduction of possible locations for the hub were significant. The hub was then used as a constrainer to refine node J. The results are shown in Figures 4.7 and 4.8.

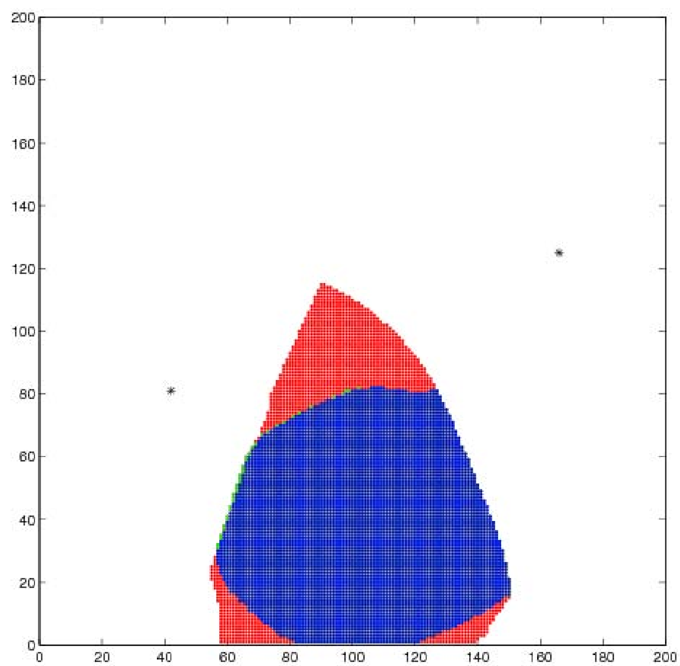


Figure 4.7: Node J through three steps of iterative refinement in Experiment #1-2

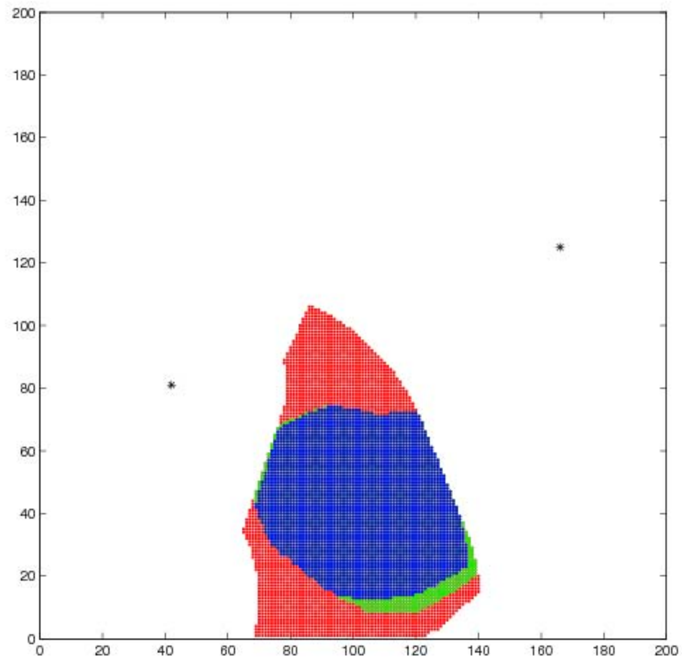


Figure 4.8: Node J through three steps of iterative refinement in Experiment #1-3

4.3 Experiment #1-1, #1-2, and #1-3 Comparisons

With the amount of refinement the hub received, results of J's MPL in Figures 4.7 and 4.8 should be refined with greater accuracy compared to Figure 4.3. However, in Experiment #1-2 and #1-3, the refinements did not show a noticeable improvement. In fact, J was actually refined less in #1-2 when compared to #1-1. The reasons for this is:

- Communication range information does not play a large role in the experiments. For example, in both #1-2 and #1-3, the range for F and the hub were the same: 40 to 80.
- F and D did not receive any significant refinement in locations from the hub due, in part, by the similar range information.

- F and D did not have any significant orientation constraints. Such closeness in the third refinement of J in #1-1, #1-2, and #1-3, suggests there is little to no additional orientation constraints placed upon F and D.

One effect the hub did have on the refinements of J is that in #1-2 and #1-3, J's center of mass appears to be closer to the ground truth in Figure 4.1. This suggests the hub did have some impact on the refinement results of J.

4.4 Scenario #2

Scenario #2 was developed with the expectation of obtaining faster and more accurate results. Three experiments using this scenario were conducted.

- In Experiment #2-1, each node has a unique communication range. Additionally each node is only in communication with two other nodes, one for each communication device.
- Experiment #2-2 is nearly identical to #2-1 except a hub has been introduced. Further significant refinement for nodes K and E should be attained by including a hub.
- Experiment #2-3 is similar to #2-2. The difference is the that RTA's are adjusted to be less restrictive to the orientation ranges of the nodes.

Figure 4.9 is the actual topology of Scenario #2. The addition of the hub is only used in #2-2. Like Scenario #1, a 200 x 200 grid is used. Differences between Scenario #1 and #2, include:

- Scenario #1 has 20 nodes (minus the hub), Scenario #2 has 14 nodes (minus a hub).
- Scenario #2 nodes have two communicators and only sees one other node through each communicator, not multiple nodes.
- When a hub is introduced in Scenario #2, it is only communicating with one one-hop node, the other nodes are at least two hops away.

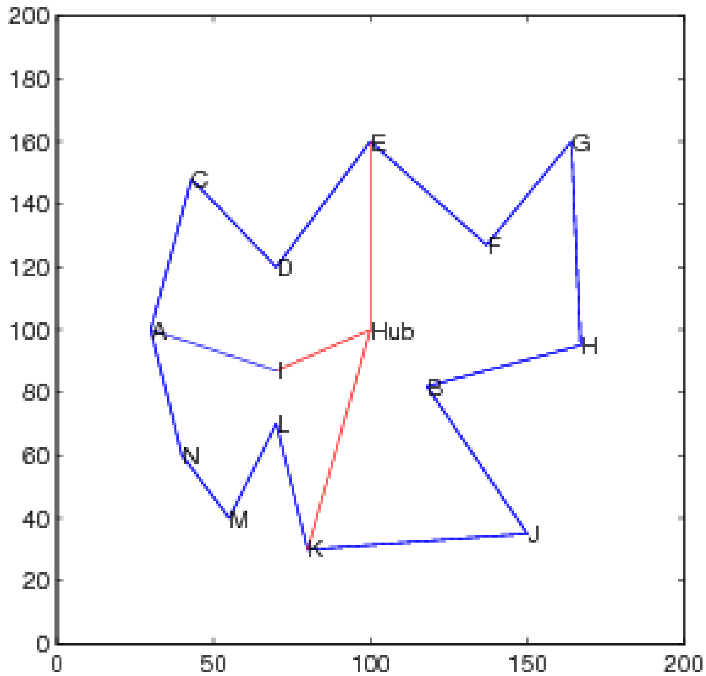


Figure 4.9: Topology for the generated specialized case

In Scenario #2, nodes A and B are anchor nodes at locations (30,100) and (118,82) respectively. Like Scenario #1, the possible orientation ranges for each anchor are between 355 and 5 degrees. Node RTA's and ranging information are in Tables 4.3 and 4.4. Table 4.3 has the configurations used in Experiment #2-1 and #2-2. Table 4.4 has the configurations used in Experiment #2-3.

4.5 Scenario #2 Results

The locations calculated for the one hop nodes in Experiments #2-1 and #2-2 are shown in Figures 4.10 and 4.11. Notice the difference in positioning of the MPL. This is not due to a change in topology, as all nodes in the network have maintained their initial ground-truth locations. The change in the MPL is a result of changing the RTA's of the nodes. This effect is seen throughout the remainder of the figures and creates some significant differences between calculations of like-node's locations.

Table 4.3: Nodes with their respective communicator boresights and ranges for Experiment #2-1.

Node	Comm 1	Comm 2	Comm 3	Min Range	Max Range
A	86	265	340	35	55
B	3	319	-	45	65
C	255	315	-	35	55
D	64	121	-	35	75
E	239	317	270	40	60
F	59	124	-	40	60
G	218	284	-	40	70
H	82	212	-	45	70
I	30	160	-	30	50
J	110	195	-	55	75
K	353	106	75	35	75
L	240	284	-	25	45
M	60	128	-	20	40
N	117	296	-	20	45
Hub	30	91	137	35	70

Table 4.4: Nodes with their respective communicator boresights and ranges for Experiment #2-2 and #2-3.

Node	Comm 1	Comm 2	Comm 3	Min Range	Max Range
A	74	277	340	35	55
B	15	307	-	45	65
C	255	315	-	35	55
D	52	133	-	35	75
E	239	317	270	40	60
F	47	136	-	40	60
G	230	272	-	40	70
H	90	200	-	45	70
I	30	160	-	30	50
J	122	183	-	55	75
K	5	106	75	35	75
L	240	284	-	25	45
M	60	128	-	20	40
N	105	308	-	20	45
Hub	30	91	137	35	70

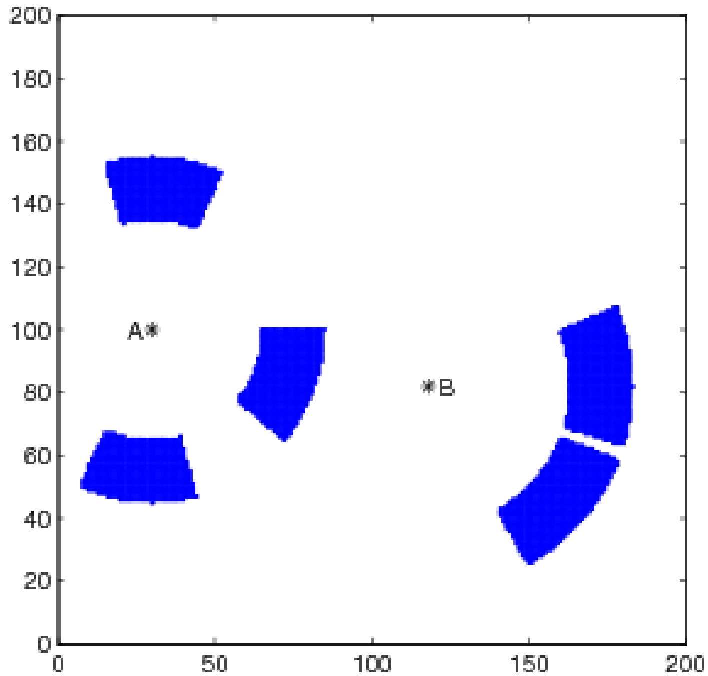


Figure 4.10: MPL for one-hop nodes in Experiments #2-1 and #2-2.

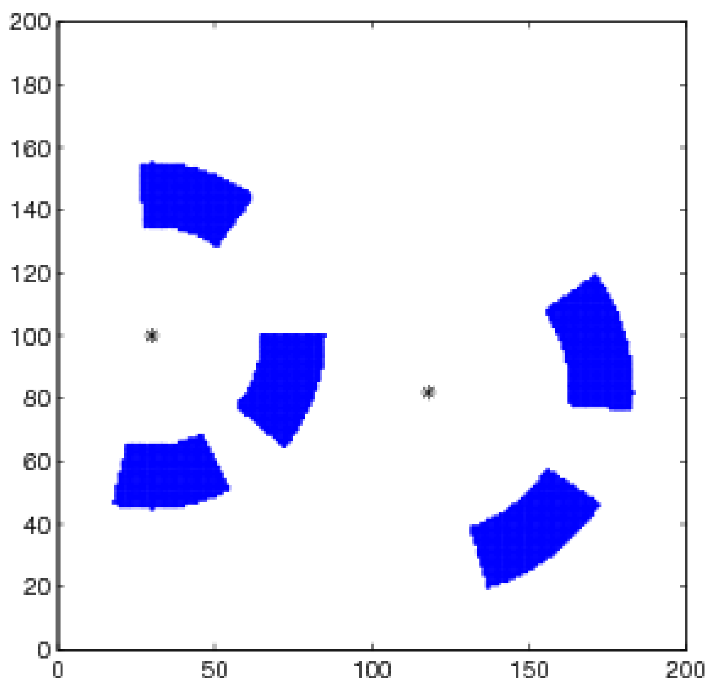


Figure 4.11: MPL for one-hop nodes in Experiment #2-3.

The locations calculated for the two hop nodes can be seen in Figures 4.12 and 4.13. The hub node, colored red, in Figure 4.12 was not in Experiment #2-1. The remaining two hop nodes are the same for both Experiment #2-1 and #2-2. In Experiment #2-3 there is a noticeable change in two-hop node's MPL from #2-1 and #2-2, due to the change that occurred in the node's RTA's.

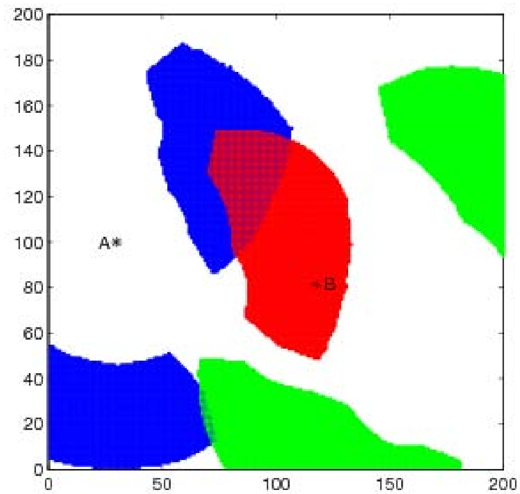


Figure 4.12: MPL for two-hop nodes in Experiment #2-2.

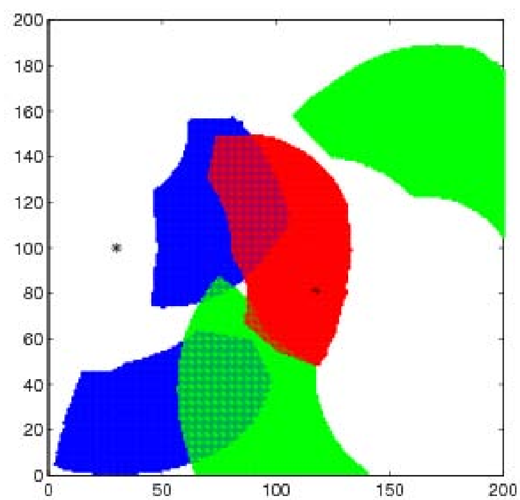


Figure 4.13: MPL for two-hop nodes in Experiment #2-3.

Figure 4.14 and 4.15 show refinements of node K from the hub node in Experiments #2-2 and #2-3. There is a noticeable difference in the final refinement shown in green due to the strong and weak constrainments of the hub in the two experiments.

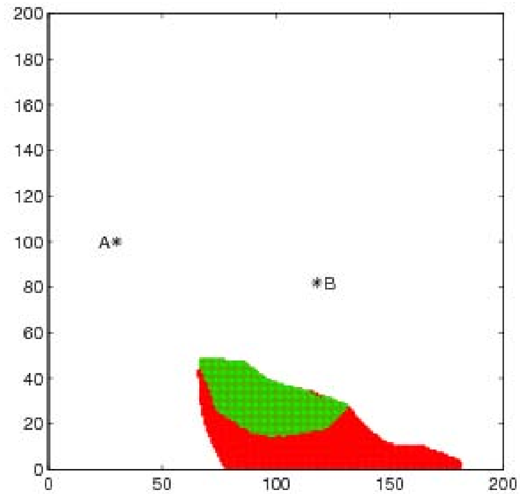


Figure 4.14: MPL for node K in Experiment #2-2

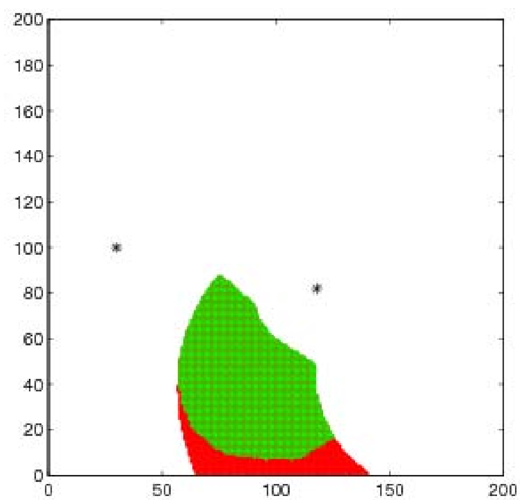
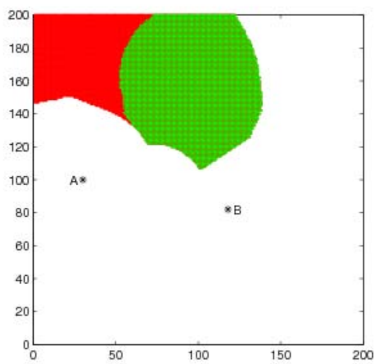
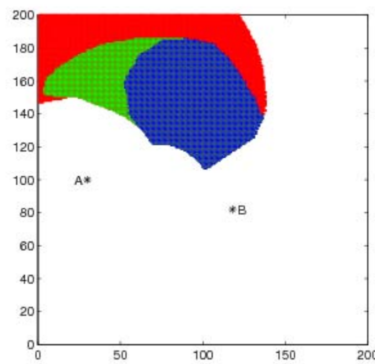


Figure 4.15: MPL for node K in Experiment #2-3

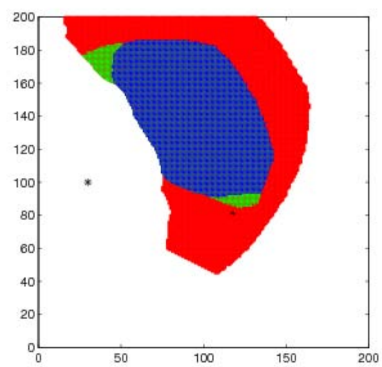
The third refinement of E is irrelevant in Experiment #2-1 so it's only potential locations are in green in Figure 4.16(a). In Experiments #2-2 and #2-3 where a hub was implemented, E's second refinement came from the hub rather than F which explains the difference in location changes for the second refinement of E in Figure 4.16(b). There is also a noticeable difference in the third refinement of E for experiments #2-2 and #2-3 due to the differences in RTA's in Figure 4.16(c).



(a)



(b)



(c)

Figure 4.16: (a)MPL for node E in Experiment #2-1, (b)MPL for node E in Experiment #2-2, (c)MPL for node E in Experiment #2-3.

In all three experiments, node F was refined by node E as seen in Figure 4.17. There is a slight difference between F's second refinement in Figure 4.17(b) from Figure 4.17(a) suggesting that including the hub did have some effect on F's MPLO. In Experiment #2-3, there is little refinement in F's MPLO even with a hub introduced since the orientations of F were not as constrained in Experiment #2-3 as they were in #2-2.

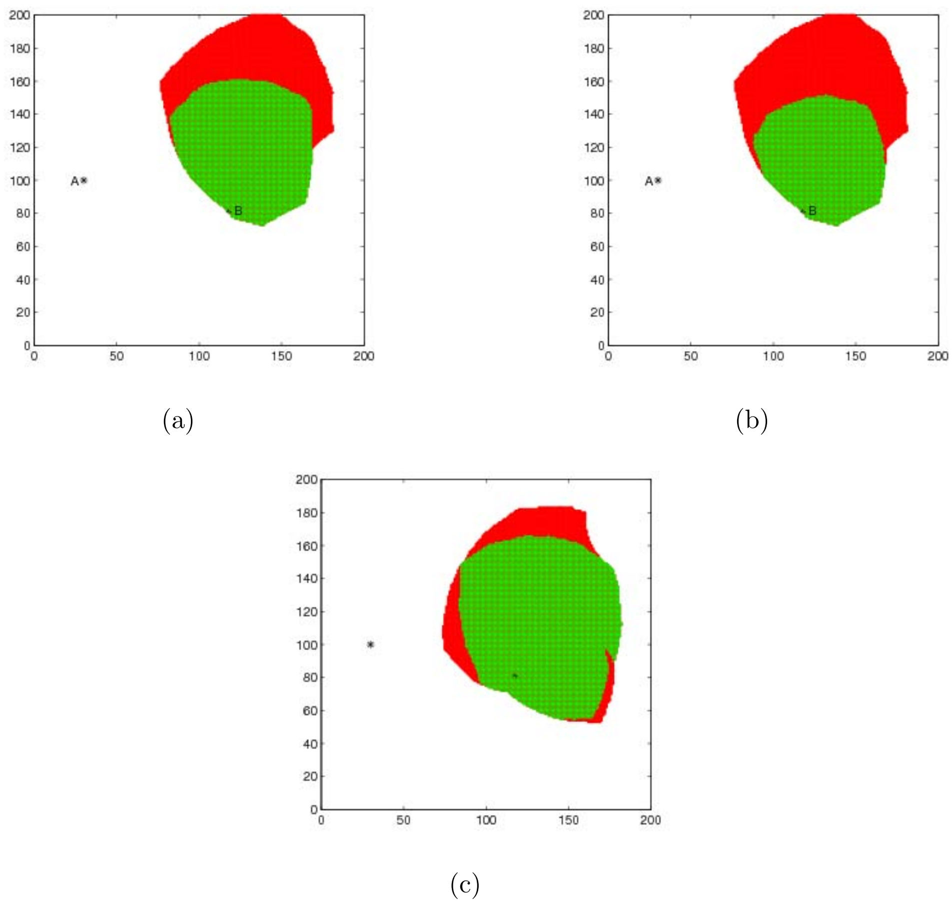
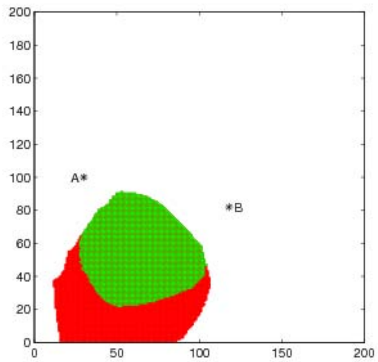
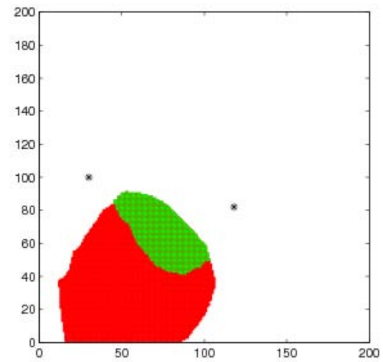


Figure 4.17: (a)MPL for node F in Experiment #2-1, (b)MPL for node F in Experiment #2-2, (c)MPL for node F in Experiment #2-3.

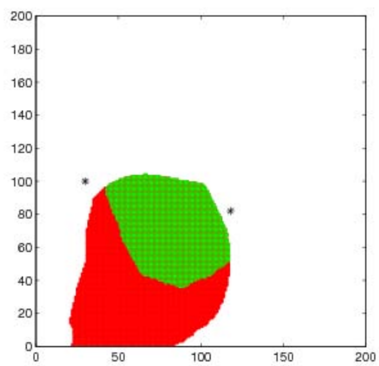
Figure 4.18 shows the refinement of L for three different experiments. Noticeable differences in each of F's MPLO are due to the experiment parameters.



(a)



(b)



(c)

Figure 4.18: (a)MPL for node L in Experiment #2-1, (b)MPL for node L in Experiment #2-2, (c)MPL for node L in Experiment #2-3.

Figure 4.19 shows the refinement of the hub's MPLO for Experiments #2-2 and #2-3. There is a very large difference in the final refinements of the hub (depicted in blue) due solely to the difference in the orientation constraints as expected. Because of the tighter orientation constraints for the hub in Experiment #2-2, there is a more dramatic refinement to the hubs MPLO from Figure 4.19 to Figure 4.20

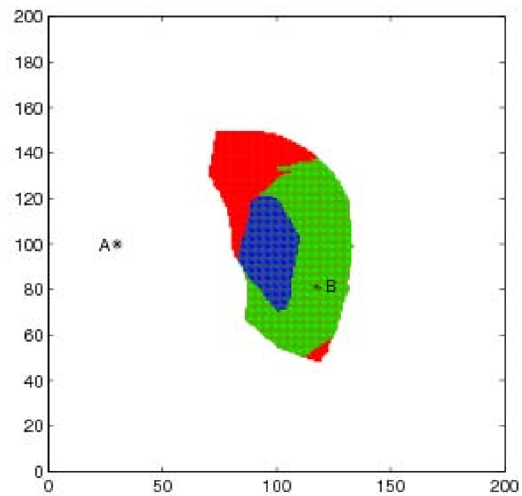


Figure 4.19: MPL for the hub in Experiment #2-2

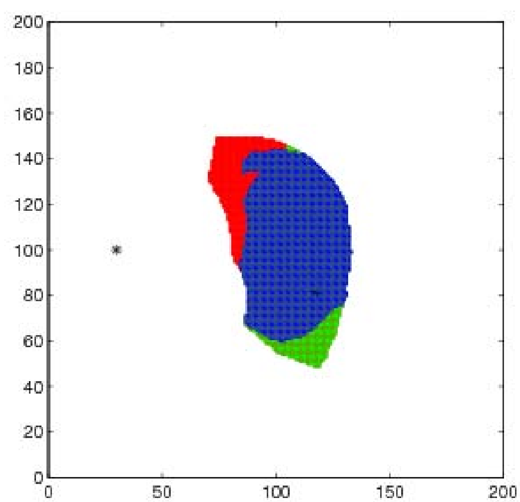


Figure 4.20: MPL for the hub in Experiment #2-3

4.6 Summary

This chapter presents directional communication localization results for experiments in two separate topologies. For each topology, two anchor nodes are defined and a hub is introduced into some of the experiments. The networks presented in each topology are connected and each node has a given communication range and RTA's. Localization of nodes with unknown locations are calculated via existing connections, RTA's, and communication ranges.

More desirable results are obtained as the amount of strong information increased. This information includes adding additional nodes, such as a hub, and new connections to selected nodes. For example, in the case of Scenario #2, a hub is added into the topology with a location at the center of the network. A hub is connected to E and K since they are at least two hops away from an anchor. This resulted in a greater impact on the localization of E and K as well as on the information obtained from E and K to re-refine the locations of nodes surrounding them.

V. Conclusions and Recommendations

5.1 Chapter Overview

This chapter draws conclusions and discusses the significance of the experimental results. Recommendations for future research in directional communication localization are also made.

5.2 Research Conclusions

The experiments for both scenarios suggest that weak information, directional communication localization is feasible in certain situations. However, the algorithm cannot attain significant results for a wide range of randomly generated topologies. The exhaustive approach to this problem is resource intensive and does not lead to results quickly. As the network topology increases, the time it takes to localize the nodes exponentially increases. In many cases, the first refinement of a three-hop node required up to four hours to complete. Couple this with additional three-hop nodes in a topology, as well as re-refinement of all nodes in the network, and the total runtime for one experiment, as observed during the experimentation phase can easily exceed 24 hours. This does not lend itself to a real-time localization tool.

5.3 Research Significance

The experiments show localization potential for very small networks. Significant refinements are seen for specialized cases such as the five node network in Chapter 3. As the network grows in size, nodes receive less significant refinement. Therefore localizing large-scale sensor networks would require excessive time and resources and be of limited use.

5.4 Future Research Recommendations

Statistical analysis would be beneficial. A specific area of interest is calculating the center of mass for the MPL of each node and calculating the error of the center of mass estimate with the ground truth locations of each node. In the algorithms

current state however, this cannot be done reasonably with a large number of varying, randomly generated, topologies as the algorithms complexity is $O(n^4)$. Additionally, the MPLO computation time of a refinee node is large due to the lack of certainty in the initially refined MPLO of a constrainer node. Consequently, this leads to another area of interest: exploring optimization techniques of the localization algorithm.

Automation of the experiment would also be useful. Doing this may, however, require a foundation in artificial intelligence. As noticed during the experimentation phase, the order of node selection for refinement impacts the overall run-time and output effectiveness. Automation would benefit from run-time optimizations if they were explored and implemented.

Another area of interest is to use communication devices that are highly directional, such as lasers, to refine nodes in a network. Much of the complexity of the algorithm is a direct result of calculating a large number of potential locations. The less ambiguity there is in a node's location, the fewer resources needed to calculate potential locations.

Finally, research could be done on mathematically formulating the shapes of the potential node locations past one-hop (as the one hop nodes are a direct product of the anchor). Doing so would alleviate much of the complexity of the algorithm implemented. If the shapes could be formulated mathematically, the need to exhaustively search locations is removed.

5.5 Summary

This research focused on directional communication to localize nodes in a network. It showed that for small networks, given particular topologies, the methods outlined in this research produce feasible results. However, as the network grows in size, the cost to localize the network is very costly. Further research in the areas outlined in the recommendations may prove valuable if significant progress could be made to further define the refinements mathematically or geometrically calculate results.

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14. ABSTRACT
Localization is the process of determining relative, as well as absolute, positions of communicating devices. Traditionally, the process is conducted using range or directional estimates. In contrast, this research uses weak information to form relatively tight bounds on possible locations of communicating devices. Under certain conditions, achieved location estimation results are strong. However, these results are highly sensitive to the operating conditions of the proposed networks. More significant results were obtained from specialized cases and that the application yields somewhat limited information for a general randomized network topology. Feasible localization results were found to be attainable but not necessarily practical for multiple experiments. This is due to the brute force nature of the implemented localization algorithm which experiences an exponential increase in runtime as the number of nodes increases.

15. SUBJECT TERMS
Localization; Directional Transceivers; Networks; Topology; Relative Transceiver Angle; Boresight Angle; Orientation Constrainment.

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